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Michael S. Rosenbaum
A. Keith Turner (Eds.)

New Paradigms in Subsurface Prediction

Characterization of the Shallow Subsurface Implications for Urban Infrastructure and Environmental Assessment

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Preface

This publication contains material presented at the Euroconference entitled "New Paradigms for the Prediction of Subsurface Conditions: Characterisation of the Shallow Subsurface and Implications for Urban Infrastructure and Environmental Assessment", together with ideas and inspiration freely shared amongst the delegates. The Euroconference was held at the Sol Cress conference centre, Spa, Belgium, 7–12 July 2001.

This Conference, the 7th in a series (Turner, *this volume*), arose from a series of meetings which began over 10 years ago, as mentioned in the introduction to Part A (*this volume*), in Santa Barbara in California with NATO sponsorship. Then followed a move to Europe with a 3D GIS focus, to Würzburg and then to Freiburg (Germany), then with ESF funding to: Lucca (Italy), Canterbury (UK) and Kerkrade (The Netherlands).

The conference offered young researchers an opportunity to explore cross-disciplinary applications of their specialised research knowledge and experience through participation in lectures, demonstrations, and poster sessions, as appropriate to their research.

An important aspect of the conference was the time periods set aside for discussion of issues by smaller focus groups, and the subsequent reporting of these discussions to the entire group of participants. Each focus group was no larger than 10 participants, so that all had a chance to raise issues. Arrangements were made to assist groups in recording their discussions. The conference organisers assigned participants to these groups, and discussion group facilitators (chairs, secretaries and reporters) were appointed, thereby assuring that young researchers were heard during these discussions.

The authors hope that the essence of the meeting has been successfully captured in this volume, enabling the delegates' deliberations to be shared with the wider community and encouraging the evolution of information technologies to better address user needs for subsurface characterisation.

Mike Rosenbaum
A Keith Turner

The editors

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Part A Fundamentals

Characterisation of the shallow subsurface during the last decade has been facilitated by advances in GIS and visualisation technologies, making possible the development of increasingly realistic 3D models of geological frameworks, systems, and processes.

But model construction typically requires a lengthy interactive procedure by which geoscientists progressively build and refine models using a considerable variety of different information technology tools. This requires enormous effort by highly trained (and therefore expensive) personnel. The models are so costly that they can be used only in a limited number of "high-profile" applications.

Despite these economic constraints, 3D subsurface characterisation has benefited many disciplines – especially those concerned with oil and gas exploration (e.g. reservoir characterisation and management), environmental assessment (e.g. contaminant flow and transport modelling), geotechnical and mining engineering studies (e.g. de-watering operations).

Publicity concerning these applications has increased demands for methods making model construction more efficient and, therefore, more affordable. Widespread use of 3D modelling should then be possible.

In 1989 one of us (AKT) was privileged to be director of a NATO Advanced Research Workshop in Santa Barbara, California, that investigated the (then) new arena of 3D subsurface modelling (Turner, 1991). The conference concluded with a series of discussions about the "state of the art" and the need for further research. Many viewpoints were expressed but, overall, they can best be summarised in three categories:

1. Things that have been accomplished reasonably well

3D visualisation was considered to be satisfactory and reasonably efficient. Basic analysis tools, such as the computation of volumes and surface areas, also received passing grades. Although there was no standardised approach, many of the systems provided attractive user interfaces, and a number of modelling techniques were supported.

2. Unsatisfied needs

Several important unsatisfied needs were identified in 1989, including:

- Lack of linkages among 3D visualisations and databases
- Inadequate representation of faults and discontinuities
- Inadequate methods for displaying inherent uncertainty in 3D models
- Interactive model creation
- Inadequate methods for displaying multiple interpretations or temporal changes within the same geometric space.

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3. Issues for which there was no consensus
Opinions varied widely concerning the cost of 3D systems, ranging from "make it cheap" to "regardless of price, it must be capable of handling complex tasks". Also, no consensus was reached concerning the desirability of having "universal" rather than problem-specific systems.

About a decade later, these statements remain substantially valid. Of course, progress has been made. Our favourite example is the graphics chip, at that time housed in an expensive UNIX workstation, but now forming the basis of the Nintendo'64 game system. This reflects about a 1,000-fold reduction in hardware price.

But, while we have much better hardware and software today, several issues remain unresolved. At the 1989 NATO conference, Dr Brian Kelk, then responsible for geo-information systems at the British Geological Survey, defined the requirements for subsurface characterisation and modelling as follows:

"The industry requires a system for interactive creation of spatial and spatio-temporal models of the physical nature of portions of the Earth's crust. i.e., the capability to effectively *model & visualise:*

- *geometry* of rock- and time-stratigraphic units
- spatial and temporal *relationships* between geo-objects
- variation in internal *composition* of geo-objects
- *displacements* or distortions by tectonic forces
- *fluid flow* through rock units." (Kelk, 1991)

The description succinctly defines the requirements that remain valid even now. It appears unlikely that there is a better short description of the problem faced by those wishing to characterise the subsurface.

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1 Characterisation of the shallow subsurface: implications for urban infrastructure and environmental assessment

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1.1 The Context

Civil and geotechnical engineering and environmental applications depend on a precise definition of the shallow subsurface. The very shallow urban underground environment, where many infrastructure and utilities elements are located, presents very difficult characterisation problems. Characterising the deeper subsurface is important for groundwater resource evaluations, environmental contamination assessments, and for some infrastructure applications such as underground storage facilities.

Subsurface geological modelling became an economic and technological reality in the late 1980's, when competing 3D geoscientific information systems were the subject of considerable research and evaluation. Integration of modelling within decision-support systems is now occurring rapidly, spurred by the evolution of the Internet and Web-browser technologies, hardware and software developments, expanded information transmission capabilities, data visualisations, and modern data base concepts. Despite considerable research being devoted to subsurface characterisation over the past decade, the pace of technological innovation has outstripped the ability of many potential users to evaluate and adopt promising new characterisation methods.

Subsurface characterisation demands the prediction of geological, geotechnical and geomechanical properties based on economic and timely exploration methods. It usually faces a lack of information about the geological framework, the engineering properties and behaviour of the materials, and the existing stress field at a given location. Even the most sophisticated of the new methods leave some uncertainty in geological interpretation. Uncertainty in geologic interpretation has been evaluated, primarily within the petroleum industry, by a variety of techniques including fuzzy logic, fuzzy clustering, and probabilistic methods (including Monte Carlo simulation and conditional probabilities). Process response models, stochastic models, and neural nets have all been investigated as part of decision support system design.

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Investigations in the shallow subsurface differ from those conducted for petroleum or mineral exploration. Shallow investigations generally require much higher feature resolution, more precise property matching, and the ability to differentiate conditions in a noisy environment; the essence of **Engineering Geology**. **Engineering Geophysics** has evolved as a sub-speciality to provide high-resolution imaging to depths of a few tens of meters. **Environmental Geochemistry** has followed suit. Traditional sampling methods are being supplemented by innovative penetrometer techniques for soft soils, and by directional drilling and coring methods. The very shallow urban underground environment, where many infrastructure and utilities elements are located, presents the most difficult characterisation problems. Characterising slightly deeper portions of the shallow subsurface is important for groundwater resource evaluations, environmental contamination assessments, and for some infrastructure applications such as underground fluid storage and deeply buried facilities.

It is becoming increasingly clear that achieving a more complete understanding of the Earth's geological systems will require ever increasing degrees of integration of data, insights, and the perspectives derived from many subdisciplines. The considerable research efforts that have been devoted to subsurface characterisation over the past decade offer a means for integrating spatially referenced data, and provide important visualisation and interpretation tools. The current systems are based on fundamental data models developed in the 1970's and 1980's – an era with a very different computer technology from that available today. The changes in computer technology, and the evolution of our concepts of information management, dictate a new evaluation of these fundamentals. Yet an important question remains: how can the use of these subsurface characterisation methods be made easier and more productive?

1.2 The Objectives

The aim has been to provide the basis for a research agenda for the next decade concerning cross-disciplinary issues with respect to the roles of geological modelling and computing science in ground characterisation. The Objectives are to:

- Explore cross-disciplinary applications of geological modelling and computing science in ground characterisation through dialogue between providers and users
- Establish how subsurface characterisation methods can be made easier and more productive
- Establish a network and one or more centres that provide the critical mass needed to realise the full potential of co-operation, synthesis, integration, and innovation for better predicting subsurface conditions
- Encourage young researchers to explore cross-disciplinary applications of their specialised research knowledge and experience.

1.3 The Issues

The chief impediments to greater use of subsurface geological modelling are:

- the lack of fully developed 3D and 4D oriented mathematical, cognitive, and statistical spatial analysis tools
- the inability of available systems to accurately depict the natural variability of geological features, or to represent uncertainties related to interpretation of spatial configuration or properties
- the lack of broad access to specialised tools for exploring and modelling geological systems. Although many such tools have been developed for the oil industry, they are too expensive or commercially sensitive for all but a few organisations to procure
- the lack of comprehensive examples that might break the 'scientific inertia'. Many scientists know about quantitative subsurface characterisation methods, but do not embrace them because they wonder if the investment in time, effort, and research funds to deal with the existing software tools will result in better science.

1.4 The Challenges

One way to motivate basic research is by posing grand research challenges. The conference is designed to address seven challenges that represent the fundamental scientific questions that will drive subsurface characterisation research in the next decade:

- The **Representation** Challenge: To find ways to express the infinite complexity of the geological environment using the binary alphabet and limited capacity of a digital computer.
- The **Cognition** Challenge: To achieve better transitions between cognitive and computational representations and manipulations of geological information – to recognise what is seen.
- The **Uncertainty** Challenge: To find ways of summarising, modelling, and visualising the differences between a digital representation and the real phenomenon.
- The **Data** Challenge: To respond to the increasing quantity of data being collected and archived, to the increasing sophistication of the data content, and to the demands of complex analyses.
- The **Simulation** Challenge: To create simulations of geological phenomena in a digital computer that are indistinguishable from their real counterparts

- The **Provider's** Challenge: The role of the geoscientist as an information provider (through the use of models) is placing increasing emphasis on the requirement to be customer-orientated; the focus is on the 'end use' of the knowledge that is being imparted – and should the Provider interpret the information? Where does responsibility lie?
- The **User's** Challenge: Ensuring the end use of a material or product is made clear – to facilitate a 'performance basis' to ensure that the model is both 'fit for purpose' and 'fit for end-use' – and should the User interpret the information? Where does responsibility lie?

1.5 The Conference

This volume has arisen from a Conference, held in 2001 at Spa, which was organised to explore the seven major Challenges just set out.

Both information providers and information users were invited to explore how the rapidly evolving and maturing data acquisition and information technologies can better address specific user needs for subsurface characterisation. The conference utilised keynote speakers from appropriate industries, while a core group of researchers interacted with different applications specialists.

An important aspect of the conference was the time periods set aside for discussion of issues by smaller focus groups, and the subsequent reporting of these discussions to the entire group of participants. It is hoped that the essence of the meeting has been successfully captured in the chapters which follow, whereby the delegates' deliberations concerning the evolution of information technologies to better address user needs for subsurface characterisation are shared with the reader.

2 Bridging the gap between geoscience providers and the user community

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2.1 Context

Though geology is now a fully recognised academic subject, its origins were as much driven by need (and greed) as detached enquiry. The industrial revolution that shaped today's world was, in large part, driven by the use of mineral resources to manufacture new products and provide the necessary energy to fuel industry and improve communications. The environmental consequences of this revolution were largely ignored in the rush to create wealth and develop society. Consequently, geologists had a key role in the location and development of the mineral resources. However, as easily located resources were depleted, geologists had to develop their understanding of the earth to enable them to locate new sources of minerals. This led to the foundation of university geology departments and the setting up of geological surveys.

Today, these twin pillars of geological advance still dominate geoscientific research and, until recently, with the start of the information technology revolution, their outputs would have been readily recognisable to 19th century geologists. However, digital systems have completely altered the nature of what geoscientific information can be provided. The user is no longer solely the professional geologist working in mining or oil and gas companies. Today, *everybody* is a user because now we are concerned far more with the consequences of our actions for our environment. We are concerned about the impact of contamination on our health, about whether ground conditions will affect the stability of our homes and the cost of insuring it and about whether climate change will increase the risk from geohazards.

Traditional geological maps and academic publications do not meet these new needs. However, the increasing availability of information in digital form and the improving access to it have revolutionised what can be provided to a wide range of users. The paper will explore this historical change both in the user demand and in the ability of geologists to provide information in useable forms. This is illustrated with reference to the development of the geological map over the last two hundred years and how it has changed from a brightly coloured rectangular piece of paper to a means, for example, for the calculation of insurance premiums.

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2.2 What is meant by geology?

Put simply, in dictionary style, geology is the study of the Earth. It is interesting to note that the definition in the Concise Oxford Dictionary is wrong, defining geology as "Science of the earth's crust, its strata, and their relations and changes." All geologists would surely agree that geology covers the whole of the Earth, not just the crust. However, the study of the Earth has many aspects to it.

It is still popularly believed that the main job of the geologist is to find energy, metalliferous and industrial mineral and groundwater resources. This is because these natural resources originate within the Earth and have to be located. Indeed, it could be argued that geology and the discovery of mineral resources were hugely influential in the development of the industrial revolution. One example illustrates this – the presence of coal, iron and building materials around Ironbridge and Coalbrookdale in Shropshire, that enabled Abraham Darby to develop the first successful smelting of iron ore using coke, which was derived from local coal. Subsequently, his grandson built the first iron bridge, after which the village was named.

The growth of geology to satisfy the increasing demand for resources by the industrialised world has seen geologists develop their research to help meet these demands. They have done this by seeking to increase our understanding of what happened through geological time so that we can build three-dimensional geological models to assist us in predicting the location of economically viable resources.

2.3 Geoscience information providers

While it is clear that geology is of key importance in wealth creation, it is also very relevant to the improvement of the quality of life. The industrial revolution, which the availability of geological materials helped to fuel, also produced an environmental legacy with which we are only just starting to come to terms. As we move into an era in which future development will have to be increasingly sustainable, so geologists are having to provide society with the information needed to achieve this. Society needs to be assured that our groundwater is safe to drink, that our buildings and infrastructure are safely constructed, that the ground that we use for building, recreation and cultivation is not contaminated and that we do not exacerbate natural geological hazards.

It is hard to know whether the first geologist was a consultant or an academic, whether s/he was concerned with solving a practical problem or simply interested in the rocks and soils around them and wanted to know more. Some of the first geologists looked at the composition of rocks (petrologists and mineralogists). Others were concerned to understand the way life had evolved through examination of the fossil record (palaeontologists), while a further group sought to classify the rocks in terms of their age and how they came to be where they are today (stratigraphers). Such geologists still practice today. It could be argued, that these geologists are mainly interested in geology for its own sake, and are less con-

cerned with whether what they do has any practical application. Their work is often described as *pure* geology, in the sense that it is not influenced by considerations other than the pursuit of knowledge. Other geologists are more concerned with the relevance of geology to improving people's lives. Such scientists are usually referred to as *applied* geologists.

Maybe this separation between those geologists pursuing knowledge and those trying to apply that knowledge wouldn't matter too much if it hadn't been for the development of a third strand for the provision of geoscientific information – geological surveys. Their creation was deemed necessary because governments perceived that it was of national importance to know what mineral resources a country possessed and in what quantities. Academic geologists were unwilling or unable to provide this geoscientific information systematically on a geographical basis, and consulting geologists did not have the financial resources to do so. Consequently, government organisations were created to meet this need and the first task of these new geological surveys was to provide geological maps covering whole countries. However, the geological map was not 'invented' by geological surveys; its development can be traced back over 3000 years.

Very few scientific disciplines have developed this three-fold division in terms of who provides society with the outputs of that discipline. Geology, however, is different from most other sciences in that most of what is done has a *spatial* dimension to it. All natural samples come from a definable point within the earth and all have got there as a result of a series of processes acting over very long periods of time. Geology is highly dependent, therefore, on being able to locate an observation on a rock in three dimensions. The geological map was devised to enable the visualisation of the relative positions of different rock samples and how they were related. Consequently, the geological map, in all its forms, has been the primary geological output for almost 200 years. It is not surprising, therefore, that in January 2000, Simon Conway Morris of the University of Cambridge, writing in Earth Heritage (a magazine on geological and landscape conservation produced by English Heritage, Scottish National Heritage, the Countryside Council for Wales and the Royal Society for Nature Conservation) put the geological map as No. 1 on his list of geology's ten key episodes of the Millennium.

2.4 The development of the geological map

2.4.1 Before 1835

It is probable that the earliest known topographic maps were produced by the Babylonians. A city plan dating from about 2200 BC is held in the Istanbul Museum while the British Museum has a clay tablet showing a representation of the world and dating from about the 5th century BC (Tooley, 1978). The earliest geologically-related map or section may be the Turin Papyrus that dates from about 1320 BC and shows an Egyptian gold mine. Other maps and sections were no doubt produced from time to time though few have survived. Most of these related to the working of minerals and are really mining maps that relate to the local geol-

ogy. Examples include those produced by Georgius Agricola in 1556. These show the traces of metalliferous ore veins and the mines sunk to exploit them. Similar mineral/mining maps were produced elsewhere in Europe. For example, maps of various Bohemian mine districts survive from the 15th and 16th centuries (Urban, 1984) and a map showing copper-bearing vein systems in Hosenberg, Germany is dated 1574 (Langer, 1984).

Wilson (1985) suggested that the "concept of cartographic illustration of geological phenomena" could be traced back to Martin Lister who, in 1684, produced maps showing sands and clays. According to Milanovsky (1984), the first true geological maps were compiled of parts of Western Europe by Guttard, Desmarest and Füchsel in the second half of the 18th century. In Russia the first map was by Lebedev and Ivanov in 1789 – 1794 for parts of the Transbaikalian Region. In Britain, the Scot John Clerk produced a number of accurate sketches of parts of Scotland in the period 1785 to 1788 (Craig, 1984). These sketches were not discovered until 1976. They included a section of Arthur's Seat and Salisbury Crags in Edinburgh, a section through the Southern Uplands and a map of Glen Tilt in Tayside. William Maton produced a "Mineralogical map of the Western Counties of England" in 1797. However, relatively large-scale, truly geological cross sections were being produced much earlier than this. For example, Strachey published cross sections of the Somerset coalfield in 1725 (Figure 2.1).

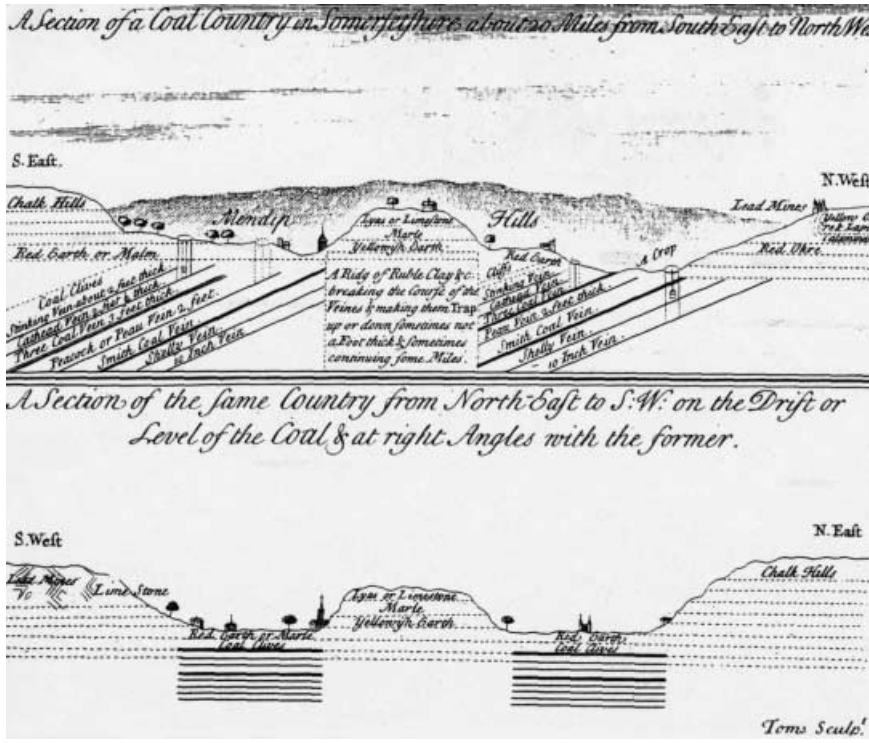
A Section of a Coal Country in Somersetshire about 20 Miles from South East to North West
S. East.
N. West
Chalk Hills
Mendip
Hills
Lead Mines
Red Earth, or Mafes.
Red Ochre.
A Drop
Smith Coal Vein.
Shelly Vein.
10 Inch Vein.
A Section of the same Country from North East to S. W. on the Drift or Level of the Coal & at right Angles with the former.
S. West
N. East
Chalk Hills
Lime Stone
Yellowish Earth.
Toms Sculp.

Figure 2.1. Cross sections of the Somerset coalfield published by Strachey (1725)

These maps from the latter half of the 18th Century differed in one significant manner from later maps: they showed the rocks in terms of their composition (lithology and petrology) rather than their age (stratigraphy). While this may seem to be of little consequence to the non-geologist, it is only by being able to distinguish rocks by their age as well as their composition that we can work out the relationships between different groups of rocks and hence begin to predict what will be found in places where the rocks are not exposed. It was the use of fossils to determine relative age and to correlate between different rock outcrops that allowed the development of stratigraphy. This major advance was brought about by William Smith in Britain and by Cuvier and Brongiart in France, though Werner in Germany had also developed similar approaches.

These few examples seem to indicate that geological map making was not a significant activity but that when practised, the maps produced related to the exploitation of minerals. It is not surprising, therefore, that, given this practical background, the beginnings of geological map making, as we now know it, coincided with the industrial revolution and its exploitation of natural resources and the rapid development of transportation networks. As the industrial revolution was strongly carried forward in Britain, it is also not surprising that many of the foundations of modern geological science were also laid down there. Amongst the pioneers was William Smith.

An interesting fact about William Smith is that he was not a geologist; rather he was a surveyor and civil engineer. He started work as a surveyor on the Somerset Coal Canal near Bath. Here the rocks were well exposed in the hilly landscape and also in quarries. Smith was able to trace sequences of rocks because he recognised groups of fossils that characterised rocks of a particular age. In 1797 he produced a small geological map of the area around Bath based on the relative age of the strata (the stratigraphic succession). It was the first map of this type and it used a topographic map as its base, a principle that has continued to the present. Smith was only concerned with the practical applications of his newly discovered approach. He struggled to write down descriptions of his work and he never joined the Geological Society of London, founded in 1807. In 1815, Smith published a geological map of England using topographic base maps provided by John Cary. The map measured 2 m by 3 m and consisted of fifteen sheets. Smith also drew a number of cross sections across southern Britain. Subsequently, Smith produced twenty one county geological maps at a larger scale.

These examples demonstrate that the production of geological maps was largely driven by firstly, the exploitation of minerals and secondly, as the industrial revolution increased the production of heavy goods, the development of transportation routes. Around six thousand kilometres of canals were built in the second half of the 18th Century and the first half of the 19th Century. In the USA, the drivers for geological development were similar. Friedman (2001) has shown how the involvement of geologists in the planning for, and building of, the Erie Canal (New York State) between 1810 and 1825 was important not only for its success but in helping to lay the foundations for geology in the USA. The work included a reconnaissance survey by geologist Stephen Van Rensselaer (1793–1871) (who was a member and President of the Board of Canal Commissioners for

many years) and a geological survey that resulted in a cross section along the canal route, by Amos Eaton (1776–1842).

2.4.2 After 1835

The Ordnance Survey (then the Ordnance Trigonometrical Survey) had been formed in 1791 to produce topographic maps of Britain and (subsequently) Ireland. When Major General Thomas Colby took over as Superintendent of the Ordnance Survey in 1820, he intended that the topographic maps should serve as the base for geological survey. Captain J Pringle was asked to form a geological branch in Ireland in 1827 but the work lapsed when it became clear that the surveyors were not adequately qualified to supply the geological information. Partly at the suggestion of Sir Roderick Murchison, the President of the Geological Society, a geologist, Henry De la Beche was recruited to the Ordnance Survey and in 1835 the Geological Ordnance Survey was formed. Richard Griffith, a Fellow of the Geological Society took over the work in Ireland and in 1845 the Geological Survey of Great Britain and Ireland was formed as an independent organisation (Owen and Pilbeam, 1992). As with the maps of William Smith and others, Murchison anticipated that the mapping would have practical benefits for "agriculture, mining, road-making, the formation of canals and railroads, and other branches of national industry."

With the development of stratigraphy and the formation of the Geological Survey, the long process of systematically mapping the UK began. Bush (1974) has pointed out that the history of stratigraphy and the development of geological mapping are inextricably linked. The latter could not have developed without the former. By the time that the whole of Britain is mapped to an acceptable standard, around one hundred and seventy years will have passed. However, it is important to understand what the maps show and why, despite the optimistic beginnings, these maps have failed to provide the modern world with the practical benefits that were anticipated. This failure is as much to do with changes in science and engineering and in society generally, as it is to do with the geological mapmakers.

As described earlier, the geological map is an interpretation of what we expect to find at the surface when agricultural soils, vegetation and buildings are removed. However, what is shown may not actually be there! Data is gathered from outcrops, by interpretation of the shape of the ground surface, from temporary excavations, borehole logs, geophysical surveys and remotely sensed data from aeroplanes and satellites. The information is plotted in its correct position in relation to the topography and the national co-ordinate system and is finally interpreted according to the latest geological theories and the knowledge and experience of the geologist. In other words, the geological map is not simply a collection of facts. Two modern geologists provided with the same sets of data would probably produce two different geological maps of the same area. It is not surprising, therefore, that maps made over a hundred years apart should look dramatically different because not only has the amount of data increased but the knowledge of geological processes, and the theories to explain them, have changed too. Bush (1974) gave an example of two maps of the Canadian Shield made in 1928 and

1958. The two maps are radically different in appearance because they are based on different theories of the origin of granite.

A further difference relates to the type of geological material that is actually shown on the geological map. Conventionally, geological deposits are divided into three broad groups for mapping purposes, based primarily on age. The oldest are 'solid rocks,' that is those formed before the Quaternary Period; then there are 'superficial' (or 'drift') materials formed during the Quaternary and partially concealing the solid rocks; finally there are 'anthropogenic' deposits such as backfilled quarries, embankments and the remains of mineral workings. In the 19th Century, maps showed the 'solid rocks' but very little else. Geological Survey geologists in Great Britain, such as Clough, Peach and Horne, were leaders in the development of the science as a result of their geological mapping in the Scottish Highlands. Peat might be depicted as well as alluvium (river valley deposits) but glacial deposits were ignored. In the 20th Century superficial deposits were added, though difficulties in working out stratigraphic sequences has limited the degree of complexity shown until recently. However, mapping techniques have remained fairly traditional and simple until relatively recently. In the last ten to twenty years, deposits relating to human activity have started to be added but, again, the depiction is limited because we have not yet fully worked out a stratigraphic system to show the relationships between the deposits themselves and how they were formed.

So, on the face of it, the modern geological map differs little, in principle, from that produced in the earliest days of geological surveys. Is this why the geological map failed to achieve Murchison's aim of practical use? Certainly, by the end of the 19th Century there is evidence that engineers and geologists were not thinking in the same way. Glossop (1969) pointed out that from about 1850 onwards, geology became increasingly neglected by the civil engineering profession. Professor Keith Turner in his inaugural address to the Technical University of Delft (the Netherlands) (Turner, 2000) quotes Boyd Dawkins from his James Forrest Lecture to the Institution of Civil Engineers, London in 1898:

"Geology stands to engineering in the same relation as faith to works.... The success or failure of an undertaking depends upon the physical conditions which fall within the province of geology, and the 'works' of the engineer should be based on the 'faith' of the geologist."

While Dawkins clearly appreciates the importance of geology to civil engineering, he does not appear to show much acceptance of geology as a science. The use of the word 'faith' could be interpreted as a throw back to the geological debates of the 18th and early 19th Centuries. At this time, there was growing concern about the biblical account of the formation of the Earth and this caused major disagreement between the proponents of the Neptunist and Plutonist theories. The former theory, espoused by Werner (1750–1817) in Germany, proposed that rocks had formed by sedimentation from a primordial ocean. These were exposed when the waters retreated to form continents. Noah's flood overwhelmed the continents and added new rock layers. Subsequent volcanic activity disrupted the continents and added more sediment. Later floods added more layers. In the Plutonist theory it was proposed that rocks were formed in fire. It was originally proposed by Abbé Anton Moro (1687–1750) on the basis of a study of volcanic islands. This alterna-

tive to Werner's ideas was taken up by James Hutton (1726–1797) who proposed that the surface of the earth was subject to two basic processes in which rocks were worn away by weathering and erosion and then re-formed and uplifted by heat and pressure. A summary account of this and other early theoretical geological controversies is given by Johnston (2000).

Dawkins' ambiguity about the work of geologists is amplified by another quotation provided by Turner (2000). This one, by Cornelius Lely, Minister of Works in the Netherlands, relates to a landslide on a railway embankment in 1892:

"...the Government has made inquiries from a few geologists who know the local situation, with the purpose of informing the engineers about the special qualities of the soils there... Of course it is not certain that the advice of the geologists could be or had to be followed... The building of a railway is not the work that you can trust to a geologist..."

It would appear, then, that the geological map, and the geologists that made them were not providing the advice and information that the founders of the Geological Survey of Great Britain and Ireland had intended. Or at least, engineers, and others, were not convinced of the value of geology. Why was this? One answer might be that the geological map, because it is, in itself, an interpretation by geologists, is not readily understandable by non-geologists. So, very quickly, the geological map had become an end in itself, rather than a way of making geological information and interpretation readily available to users. Academic geologists in our universities did little to alter this direction as they became increasingly interested in 'pure' geology and soon forgot its practical roots.

2.5 The users and their needs

Geologists collect data in the laboratory, on site and in the field. They organise the data and make it available to others, so creating information. They interpret the information using their expertise so producing knowledge, which they communicate to others. For academic geologists, many of whom are 'pure' scientists, the principal outputs of their work are academic publications and presentations at conferences. The main users of their work are other geologists, both academics and consultants. For most of their existence, the main users of geological survey outputs were governments and academic and consulting geologists. The principal output was the geological map. These geologists readily understood the map, even though, as indicated above, other professional users struggled to make sense of it. Consulting geologists, whether employed within companies or brought in from outside, had the job of interpreting the geology for the use of the client or company. In the mineral resource industry, this process worked well because geology was a large part of what the companies were about. Their function is to find commercially viable minerals, process them and sell them and they employ many geologists. Over hundreds of years the relationship between the academic geologist trying to understand geological processes, the survey geologist providing spatially referenced information and the consulting geologist using these two outputs to help them locate mineral resources has worked reasonably well in creating *wealth.*

However, as we have got richer we have become increasingly concerned about the *quality* of our lives. We no longer accept 'Acts of God' as inevitable. If our houses are damaged or fall down because of landslides or swelling and shrinking clays we want to know why, we want to reduce or eliminate the risk of financial loss and we want our buildings and structures to resist the effects of geological hazards. We are concerned not only to have water to drink and wash with but also that this water is clean and does not cause us to fall ill. We no longer accept that the waste products of our society can be dumped anywhere; we want reassuring that the disposal sites are safe, that they will not leak and pollute the places where we live. We welcome improvements in our urban environment but we insist that the residues left from previous activities are removed or sterilised. We want our activities to become more sustainable so that we do not consume all the resources but ensure that we leave a viable world for our children.

The task of ensuring these quality objectives are met falls not to geologists but to other professional groups such as environmental scientists, engineers, planners, developers, financiers, surveyors, insurers, estate agents, lawyers and politicians. These non-geological professionals all require information and knowledge about the ground to enable them to perform their functions as developers of the built and natural environment and regulators of that development. However, the geological outputs that served the mineral resource industry so well have failed to be of much use these groups. Also, these groups have largely failed to realise how dependent they are on a sound appreciation of the ground conditions and, as a result, have employed few geologists within their organisations. As was indicated above, even civil engineers, who have a long history of working with geologists, still seem to have either a lack of understanding of the importance of geology or a lack of confidence in the ability of geologists to provide that knowledge. In the UK, it is still more likely that a site investigation will be specified by a structural engineer or an architect, than by an engineering geologist or a geotechnical engineer.

It can be argued, that one of the main reasons for this state of affairs is that the geologist has not yet adapted to meet these new needs and that the outputs, as epitomised by the geological map, are inappropriate for this group of users. For geological surveys that produced the maps one of the main problems was that while medium and small scale geological maps were of great value to resource geologists, environmental concerns tended to be much more site specific and maps were needed at larger scales. Consequently, the role of Surveys in relation to geotechnical engineering, waste disposal, contaminated land, geohazard mitigation and, particularly planning, was less clear.

2.6 The evolution of the geological map to meet new user needs

In the UK, two events were hugely influential in changing the form of the geological map to meet the needs of the new user groups. First, in 1948, the British Geotechnical Society was formed and the journal 'Géotechnique' published. In his forward to the first part Terzaghi (1948) stressed the importance of engineering

geology and emphasised the need for observation as well as theory in civil engineering. These events led to the development of engineering geology as an important sub-discipline of geology in the UK and the establishment of four Master of Science postgraduate courses in engineering geology in the 1960s and 70s (at Imperial College, London and Leeds, Durham and Newcastle Universities). The Engineering Group of the Geological Society was formed in 1964 and in 1967 the British Geological Survey (then the Institute of Geological Sciences) set up an Engineering Geology Unit. In 1972, A Working Party of the Engineering Group of the Geological Society published a report on the preparation of engineering geological maps and plans and on soil and rock classification (Anon. 1972); this was followed by a more theoretical report on engineering geological maps and a further report on soil and rock classification, both by the International Association of Engineering Geology (Anon., 1976, 1981). These reports established international standards for applied mapping.

The second significant event was the publication in 1972 of the Rothschild Report into the funding of science in British research centres and surveys. This report recommended that approximately 30% of the core funds be transferred from the centres and surveys to central government departments which would then 'commission' work back from the centres and surveys. Previously, the amount of applied geological mapping carried out by the British Geological Survey had been minimal. Most mapping was of the traditional stratigraphic type. As far as the development of geological maps was concerned, two significant commissions were placed. Though work had begun before Rothschild, the Department of Trade and Industry (DTI) took over funding of the geochemical survey of Britain (G-Base). This involved the collection of stream samples on a regular grid basis starting in the northernmost parts of Scotland and systematically working southwards. Samples were analysed for a range on elements (mainly metals) and element distribution maps were published. The objective was to provide background levels of these elements to assist in the identification of potential mineral resources. During the work (which has now reached the English Midlands) the emphasis switched from the identification of resources to environmental concerns over the distribution of potentially contaminating elements. In addition, urban centres, that had initially been excluded, were covered but at higher sampling densities. This change from a resource-based to an environmental-based approach has been highly significant to the development of geological maps in the UK in the latter part of the 20th Century.

The second important commission was from the Department of the Environment for engineering geological mapping of the site and hinterland of the then proposed third London airport in south east Essex. A suite of more than forty maps and sections of a wide variety of types was produced (Anon., 1977) and experiments made into some forms of digital geological contouring (Coe and Cratchley, 1979). The intended users of the report included both civil engineers and planners. This work led, a few years later, to a fifteen year programme of applied geological mapping of urban areas for planning purposes. The outputs of this programme have been described by Culshaw et al., (1988, 1990) and Smith and Ellison (1999). However, the key point about it was that the maps were specifically produced to meet the needs of the planner, as specified by planners. An addi-

tional output was a regional landslide mapping project in the South Wales Coalfield that identified a specific problem, relevant to planning in that area (Conway et al., 1980).

These applied geological maps were very varied to meet the user need. They formed the basis for the subsequent blossoming in the 1990s, when computer power and programmes had developed to address the demands of spatial data, of a whole new range of digital maps. Some examples of this new world of geological maps are discussed below.

2.6.1 Digital geological maps

It has been indicated above that the basic stratigraphical map has remained largely unchanged in its content since the 19th Century. However, the advent of computer hardware and software able to deal with the large files associated with maps has changed the nature, and potential, of these maps dramatically.

A map consists of *points*, *lines* and *polygons*. *Points* on a map represent a location that can be defined in three dimensional space, that is, it can be located in relation to some arbitrary point of origin. For example, the equator defines zero degrees of latitude (northings and southings), the Greenwich meridian defines zero degrees of longitude (eastings and westings) and sea level defines elevation (height above or below sea level). On a topographic map grid co-ordinates and contours are ways of defining a point location. A *line* links two points. On a topographic map a road might be represented by a line. A *polygon* is an area of any shape wholly enclosed by a line. A field with its hedge-line represented by a line is an example of a polygon. On geological maps, points might be locations where measurements were made or samples collected, lines might represent faults and polygons are areas underlain by one stratigraphic or lithological unit.

Modern computer software allows us to hold point, line and polygon data digitally. Consequently, we are able to hold all aspects of a geological map in digital form. In addition to the points, lines and polygons, the software also allows us to hold other information that we could display as text, data tables, photographs, diagrams etc and which can be attached to the point, line or polygon. We can call up this additional information when we use the digital geological map. On a paper-based map this additional information is referred to as the 'key' or 'legend.' However, the amount of additional information that can be provided is limited by the area of paper available to print the information. With a digital map, the amount of additional information that can be included is limited mainly by the time taken to input and check the data and the capacity of the computer hardware and software to store and process it.

This ability to hold additional information in a digital map system opens up new possibilities. A digital map that is simply a display on a computer screen of what could also be presented on paper does not represent much of an advance. The geological map differs fundamentally from a topographic one. Unlike a topographic map, which is a scaled down representation of a part of the Earth's surface, the geological map is a two dimensional representation of a three dimensional object – the ground beneath the surface. Furthermore, only a tiny amount of the sub-

surface is observable by the geological mapmaker. Consequently, the map is not a *representation* but an *interpretation* of what is in the Earth. So, the geological map is an interpretation of the three-dimensional geology and, as such, is a synthesis of a lot of different data types. Sometimes a paper-based map will include a cross section of the geology, which is an interpretation of the geology on a vertical plane. Because of the lack of space, only a few sections can be printed on paper and these sections may not be in the places of interest to the map reader. If the computer-based map simply reproduces these cross sections on a screen little has been added. However, the ability to hold additional information allows us the possibility of producing a cross section in any direction that we chose. By adding information from boreholes, for example, we can create cross sections that link these boreholes together. In most of the major urban areas of the UK thousands of boreholes have been sunk in the last fifty years. The British Geological Survey holds the logs of around 900 000 of these boreholes. Consequently, there is a huge resource of information that can be made available, provided that we can find the resources to digitise and check it.

A further advantage of the digital geological map is that it can be updated regularly. Paper-based maps, if updated, can only be made available by reprinting. This is expensive and also makes the existing unsold maps redundant. However, it is likely that many decades will pass between updates. For some remote areas, the current map may be up to 150 years old! With the digital map this situation changes. The map can be updated every day and when a user requires a copy they can have the latest version. If the map changes, it is easy for them to obtain the updated version, either in digital form, or printed onto paper. Of course, the user is no longer restricted to receiving a map of a rectangular area. Any outline can be specified, such as a local authority boundary.

2.6.2 Applied geological mapping

Perhaps the most important benefit of the digital geological map is that it allows the geologist to recast the basic geological information into forms that are understandable to new non-geological users. Two examples are presented here, one a suite of applied geological maps intended primarily for planners and civil engineers, the other an information system for use by insurers. Both have their basis in the old fashioned stratigraphical map and neither could have been easily produced without the availability of digital technology. Neither is now state of the art even though both are less than ten years old.

2.6.2.1 Wigan

As indicated earlier, in the late 1970s a programme of applied geological mapping was begun by the then Department of the Environment. The first project covered Bristol and the last (in 1996) the Bradford Metropolitan area. The penultimate project covered the Wigan Metropolitan Borough. The output consisted of two reports and ten maps. A technical report described the geological data collected, discussed the implications of the geological conditions for the area and presented the infor-

mation in a comprehensive and structured format. This report was supplemented by a database that indexed the various relevant sources of geological data for Wigan. Nine of the ten maps accompanied this report. The content of these maps indicates how the requirement of geological maps has changed in the last twenty years. Two of them are consistent with the traditional style of litho-stratigraphic maps. These maps, showing the bedrock (solid) geology and the superficial (drift) geology, underpin the other maps, forming the basis for the derivation of many of them. In other words, many of the other maps use some, or all, of the linework from the stratigraphic maps but then describe the different areas enclosed by the lines (polygons) in ways that are appropriate to the theme being covered.

The themes covered by the nine maps are indicated in Table 2.1, together with an explanation of the nature of the theme and the intended users. The themes covered indicate the nature of the geological issues that are important in Wigan. Elsewhere, other issues might be more important and so alternative or additional maps might be produced. For example, in Bradford, where similar work was carried out (Waters et al., 1996) landslides are a potential problem. As a consequence, mapping focussed on this problem and the number of known landslides increased from around twenty to over two hundred. A map showing the extent of landsliding in relation to the steepness of the ground was included as one of the thematic maps.

Table 2.1 Content and principal users of thematic geological maps of Wigan (Source: Forster et al., 1995)

Theme	Content	Examples of users
Bedrock geology	Extent and litho-stratigraphy of bedrock	Geologists and geologically literate professionals
Superficial geology	Extent, thickness and lithostratigraphy of superficial deposits	Geologists and geologically literate professionals
Distribution of pits, boreholes and site investigations	Locations of subsurface boreholes, pits and indirect measurements	Geologists and geologically literate professionals
Hydrogeology	Surface and ground-water features, water abstraction points and aquifers	Planners, water companies, waste disposal companies
Mineral resources	Potential and exploited mineral resources	Planners, mineral companies
Distribution of made and worked ground	Extent and types of made ground, waste materials, landfill and other modified ground	Planners, geotechnical and geo-environmental engineers
Previous and present industrial uses	Potentially contaminating and general industrial land use, past and present	Planners, developers, financiers geotechnical and geo-environmental engineers
Engineering geology	Geotechnical characteristics and likely engineering behaviour	Planners, geotechnical and geo-environmental engineers
Shallow mining	Extent of opencast and subsurface mine workings, mine	Planners, developers, geotechnical and geo-

entries	environmental engineers

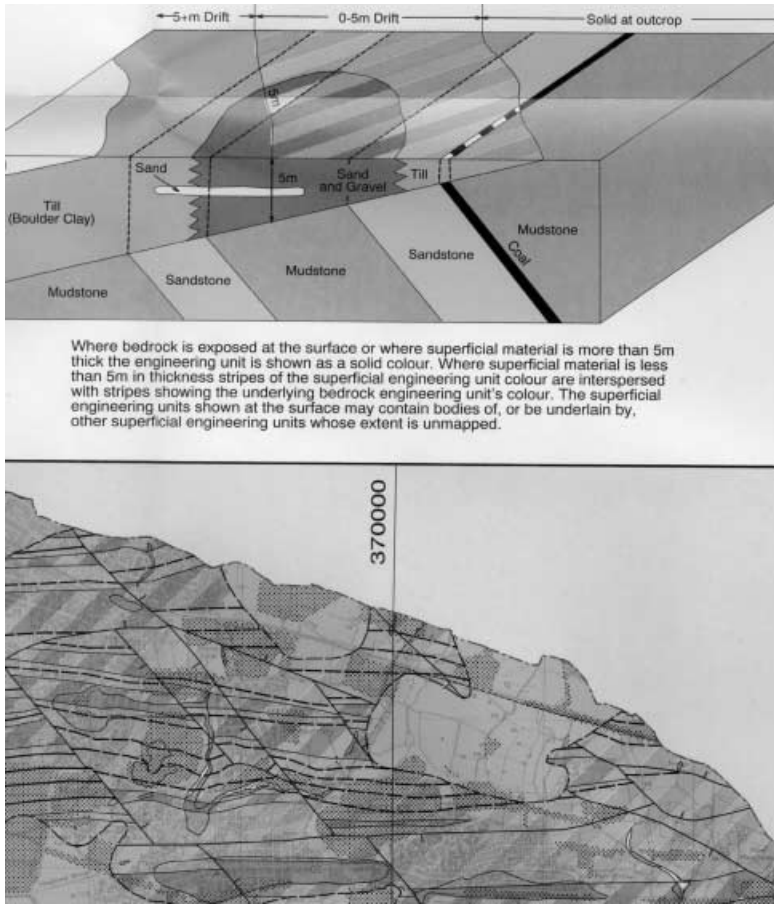
5+m Drift
0-5m Drift
Solid at outcrop
Sand
5m
Sand and Gravel
Till
Till (Boulder Clay)
Mudstone
Sandstone
Mudstone
Sandstone
Mudstone
Coal
Where bedrock is exposed at the surface or where superficial material is more than 5m thick the engineering unit is shown as a solid colour. Where superficial material is less than 5m in thickness stripes of the superficial engineering unit colour are interspersed with stripes showing the underlying bedrock engineering unit's colour. The superficial engineering units shown at the surface may contain bodies of, or be underlain by, other superficial engineering units whose extent is unmapped.
370000

Figure 2.2. Extract from the BGS applied geological map for Wigan – ground conditions (1995) *[Crown Copyright British Geological Survey, 1995]*

The second report provided a guide to the ground conditions in Wigan for non-geological users, mainly planners. This report was written largely by *planners*, rather than geologists. It provided an analysis of ground conditions in the context of the planning and economic factors that operate in the Wigan area. This analysis considered particularly:

- the extent of derelict land
- the means of, and proposals for, remediation of such land
- the impact of adverse ground conditions on development costs

- the relationship between ground conditions, economic development policies and potential grant aid.

The second report was accompanied by the tenth map that showed the key geological factors relevant to planning and development. These factors were:

- abandoned shallow mineworkings
- the potential for contamination of land by past and present industry, including landfill sites
- the potential for groundwater contamination
- mineral resources
- major faults that might act as pathways for the transmission of gases and liquids.

The ten maps in the whole report illustrate well the way in which the traditional geological map can be used to produce new geological maps that provide a wide range of information to a range of users (Figure 2.2).

2.6.2.2 Geohazard maps for the insurance industry

The late 1980's and early 1990's was a period of abnormally low rainfall across many parts of the UK, but particularly in south east England. This area is underlain by a number of stratigraphic units that consist mainly of clay, in particular the London Clay that underlies large parts of London and its hinterland. Clays tend to swell (increase in volume) during wet weather and shrink (reduce in volume) during dry periods. As a result of the prolonged period of dry weather the clays in south eastern England shrank more than usual. The shrinkage was exacerbated by the increased moisture requirement of trees and shrubs during the dry weather. The excess shrinkage of the ground removed support to the foundations of lightweight structures, particularly houses, causing damage to both foundations and super-structure. In the period 1989 to 1991, insurance companies lost around £1.5 billion in paying out claims.

Swelling and shrinkage of clay soils are not the only hazards that cause damage to property and financial loss. Dissolution of gypsum in the Ripon area has caused losses of several million pounds while the Holbeck Hall landslide on the coast just south of Scarborough destroyed a hotel worth about £2M. Landsliding at Nefyn on the north coast of Gwynedd, North Wales has not only destroyed two houses but also killed one person and seriously injured another on 2 January 2001. Collapse of abandoned mineworkings has destroyed or damaged houses in Reading, Newcastle and Edinburgh in the last few years while long-abandoned mine shafts are regularly discovered adding to the cost of development by the need to safely cap them.

These losses led insurance companies to demand an information system that could help them reduce losses by enabling them to set premiums at an appropriate level for the geological hazards found in each part of the country. The principle by which insurance largely operates is that the many pay for the misfortunes of the

few. The system is based on the idea of social justice. However, the principles of natural justice suggest that those who are at higher risk should pay more than those at lower risk. Consequently, the premium paid by an individual is based on the exposure to risk of a group of individuals. The problem is to group together individuals so that the premiums paid reflect that level of risk.

In terms of the risk of building damage from geological causes this means that what is required is a system that identifies the degree of susceptibility of geological hazards for defined geographical areas. A convenient way to do this is on the basis of address and, in particular, the areas defined by the postcode. Each part of the postcode (for example, NG12 5GG) represents a different size area enclosing smaller defined areas. The largest division is the postcode *area* represented by 'NG.' There are about 120 postcode areas in Britain. The next level is the postcode *district* (NG12). There are almost 3 000 of these. Each postcode district is divided into one or more *sectors* (NG12 5) of which there are over 9 000. Finally, each sector is divided into *unit* postcodes, represented by the full postcode (NG12 5GG). There are almost 1.6 million of these. As insurers classify addresses by postcode anyway and postcode boundaries are available digitally and regularly updated, they form the ideal basis for an address-based geohazard information system.

To provide the information needed by insurers, the geology, as represented on the lithostratigraphical map was interpreted in terms of susceptibility to six geohazards:

- landsliding
- shrinkage and swelling
- dissolution
- cambering and gulls
- shallow undermining
- soft, compressible soils.

Hence, a map was produced, in digital form, showing the extent of ground susceptible to each of the six hazards. However, such a map does not distinguish between areas of lesser and greater susceptibility to each hazard. To provide this analysis a quantitative 'total hazard rating' was determined for each of the 9 000+ postcode *sectors*. This was done by taking into account the local geological conditions within each sector using geological data, knowledge and experience. The result was a database containing information for each postcode sector. Each geohazard was analysed separately and the results of the analysis combined to produce the final sector rating taking into account possible interactions between geohazards.

The sector rating values fall in a range between 0 (no geohazard) and about 180 (high susceptibility to geohazards). The rating values can be plotted on a digital map by establishing a series of classes representing rating value range (for example, 0–20, 20–40, etc.). Each class can then be represented by a different colour or shading. Each company can decide the level of premium that it wishes to charge

depending on the geohazard rating for the postcode sector. Insurers can also determine their level of exposure (their potential liabilities) by comparing the locations of the properties insured with the variation of geohazard rating.

By providing the information in digital form users can combine the geohazard data with other spatially-defined data (for example, the distribution of fires, or burglaries) to derive a more equitable approach to buildings insurance.

2.7 The general public

The discussion above has focussed mainly on geological and non-geological professionals. However, a third group of users of geological information is developing – the general public. A minority of the public has always been interested in geology as the number of local geological societies testifies. Fossil hunting has been a popular past-time for many generations. In recent years the ever-expanding number of television channels has resulted in geology having increased coverage. It would seem that the most popular programmes are those covering fossils and those highlighting geohazards. Indeed, during the writing of this paper in May and June 2001, a topical and mainstream current affairs programme devoted a quarter of its one hour output to increased landslide activity and coastal erosion in Britain. Another mainstream channel presented several one hour live programmes on searches for fossils (particularly dinosaurs) on the Isle of Wight.

At the same time, the increasing availability of access to the Internet has led to an increasing demand for information about land, particularly with regard to property transactions. Geological surveys and others are increasingly able to provide digital interpreted information with regard to geohazards and foundation conditions for the whole of their national territories. This information is then licensed to commercial information providers who combine it with other spatially-defined information and make it available over the internet either free (at a very simple 'yes/no' entry level) or at fairly low cost (a few tens of Euros). The information is often accessed through entry of a postcode (zip code) rather than a full address. As there are over a million housing transactions in the UK each year it seems likely that the demand for this sort of geoscientific information will continue to grow.

However, the provision of such information to the general public puts an onerous obligation upon the information supplier. To avoid potential charges of negligence, the information system must be kept up to date as new information becomes available. Also, experience over the last decade has shown that while, at first, the geologist can provide more and better information than the public demands, expectations increase quickly and may very soon outstrip what is available. What has happened is that with the availability of fast digital systems and investment in the digitisation of information gathered over hundreds of years has enabled geological surveys and others to 'cash-in' on their historical databases. However, increasing awareness and hence demand has brought about a realisation that in all those hundreds of years we have not necessarily been collecting the right sort of information to meet modern demands. This is not surprising if it is remembered that geological surveys were created to collect information for min-

eral resource identification, rather than to resolve environmental problems. Consequently, a new phase of geological surveying and data collection must begin to meet these demands. In the past, the user priority in providing geoscientific information was probably: 1st academic geoscientists, 2nd professional geoscientists, 3rd other professionals, 4th the general public. If geoscience is to continue to receive government support for research and training, then perhaps this priority has to be reversed. We have the means to do so, but have we the will?

2.8 Conclusions

There is a certain irony that, just when many national geological surveys are completing the stratigraphic mapping of their territories, when there is a greater awareness than ever of the requirement to meet diverse user needs and when the information technology revolution will enable the former to become easily available to the latter, the relevance of the geological survey as an active and dynamic service organisation is being questioned. It is almost as if the realisation that the rectangular-shaped, paper-based geological map, as we knew it, is an anachronism has made decision-makers believe that, maybe, the geological survey, too, is outdated. Nothing could be further from the truth.

Increasing concern by the general public and by other non-geologists about the present and future state of our environment has provided a whole new range of users for geoscientific information. It has been argued here that, instead of the academic geologist being the most important user of geological outputs and the general public the least, the order should be reversed. As we move from the industrial to the information age and from an emphasis on mineral resources to one on the environment, so geologists must adjust to the new priorities. This new relevance would have come as no surprise to our predecessors in the 18th and early 19th centuries. Geology is coming home!

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3 Definition of the modelling technologies

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3.1 The Context

Civil and geotechnical engineering and environmental applications depend on a precise definition of the shallow subsurface. Over the past decade, or slightly longer, a series of sophisticated three-dimensional modelling technologies have been developed to address this subsurface characterisation need.

Currently available commercial modelling technologies reflect their historical origins. Further evolution and integration of these technologies within corporate decision-support systems are occurring rapidly, spurred by hardware and software developments, modern data base design concepts, and expanded information transmission capabilities across the Internet.

The very shallow urban underground environment, where many infrastructure and utilities elements are located, presents very difficult characterisation problems. Characterising the deeper subsurface is important for groundwater resource evaluations, environmental contamination assessments, and for some infrastructure applications such as underground storage facilities.

3.2 Principles of geological characterisation

The process of geological characterisation involves the determination of spatial variation, in the subsurface, of selected geological parameters. Petroleum exploration has for some time emphasized the use of seismic data, almost to the exclusion of alternative data sources. Other applications areas, including the mining, engineering, hydrogeology, and environmental restoration fields, already routinely use a broad suite of data sources. They also have a more integrated approach to three-dimensional subsurface characterisation. Thus it is usual for samples and direct observations to provide only isolated data points. Spatial prediction and interpolation techniques must then be employed to determine the three-dimensional geometrical, or spatial, patterns of geological entities.

Raper (1989; 1991) defined key concepts for subsurface characterisation and modelling - the ability to define and manipulate "geo-objects". Raper defined two types of geo-object. The first type, specified as a "sampling-limited geo-object",

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could be any discrete physical entity, such as a rock layer or fault block. The ability to locate and manipulate such objects accurately in the subsurface largely depends upon the frequency of observation and sampling. The second type of geo-object, specified as a "definition-limited geo-object," represents a spatial volume defined by the distribution of a threshold parameter. A pollution plume, an ore body, or a sedimentary facies would be examples of such geo-objects. The ability to evaluate and manipulate such objects accurately in the subsurface largely depends upon having knowledge of the parameters controlling their definition.

After a suitable geometrical representation of the geo-objects has been achieved, additional spatial interpolation techniques may then be used to identify discrete volumes containing these geo-objects and to develop appropriate spatial variation patterns describing properties within the geo-objects. Subsequently, such models can be used to provide volumetric distributions of measured attributes needed to conduct numerical processing and/or predictive modelling. Management alternatives can be evaluated, for example, once fluid migration pathways and volumes are determined, or once the distribution of geotechnical properties can be determined (D'Agnese *et al.*, 1997).

The volume and complexity of many datasets make it difficult to accomplish such integrated evaluations. Three-dimensional visualisation makes it easier to decipher trends and correlations. It allows geoscientists to explore multiple hypotheses and suggest new ideas regarding the nature of their data, often providing new insight and understanding.

To date, three-dimensional subsurface characterisation and modelling has been generally restricted to one of the three following situations:

- geometrical representation of subsurface "geo-objects"
- visualisation of spatial heterogeneity estimated by simulation
- pre- and post-processing of data for use in numerical models.

Unfortunately, such applications are each best served by different data representations. Because existing three-dimensional modelling systems are still evolving, it is not unusual for an application to require the use of multiple systems. However, data conversion between systems is usually difficult, thereby discouraging all but the most persistent users from fully using the available technologies.

3.3 Initial Developments

The Experimental Cartography Unit (ECU) was established at the Royal College of Art in London in the early 1970's. The ECU experimented with the production of topographical, geological, and geochemical maps in co-operation with the then Institute of Geological Sciences (now the British Geological Survey, BGS) (Rhind, 1988). Production of their 1:50,000 scale map of Abingdon, UK, was thus probably the first standard series multi-colour geological map ever compiled using

a computer. It also revealed the difficulties of matching geological and topographical features (Rhind, 1971).

Such early efforts concentrated research on automating the cartographic process. Subsequently it was realized that computer technology could offer much more: the true power of computer technology lay in its ability to store, manipulate, and display spatial data. Geographers were greatly attracted by the abilities of the (then still crude) cartographic software to display their data, describing social, economic, and physical phenomena. Their efforts laid the groundwork for the evolution of Geographical Information Systems (GIS).

Concurrently, the many disciplines involved in the rapidly evolving environmental movement were attracted to map overlay techniques offered by the cartographic computer-based software, for instance to identify areas where phenomena coincided and so defining suitability for, or sensitivity to, proposed activities. Landscape architects brought such an approach to a wider public, most notably in the book "Design With Nature" (McHarg, 1969). Although initially based on a manual process comprising the overlaying of map transparencies on light tables, computers and early GIS systems were soon used to carry out such tasks rapidly, and with precision.

During this period there were no readily available commercial products to provide the generic tools needed for handling spatially distributed data (Rhind, 1981). This changed dramatically in the 1980's. Broad commercial acceptance of GIS had been achieved in North America by about 1988, and this initial acceptance rapidly expanded worldwide over the next few years. The term "Geographic Information System" (or "Geographical Information System", especially in Europe), along with its acronym "GIS", became widely adopted.

However, geological exploration applications formed only a very small part of the global GIS market. Consequently, geological GIS applications had to adapt to a generic set of tools that only partly addressed their specific needs. In some cases, these needs could be readily satisfied, either by adapting the existing GIS tools, or by developing customized software modules. For example, specific software modules were developed to assist in the acceptance of common data formats, and symbol sets were provided to create traditional map displays.

3.4 Categories of GIS

Driven by technological and economic considerations, the early commercial GIS products developed with two competing data structures, termed "raster" and "vector". Some early systems tended to support the raster data structure; others supported the vector data structure. Only later did the computer technologies allow for surviving commercial GIS systems to equally support both data structures.

Raster GIS represent the study area with an array of small, uniform-sized cells, usually square or rectangular in shape. Each cell is coded to reflect the dominant value or class of the map feature being represented. Spatial relationships are readily derived from the positions of the cells within the matrix or array. In contrast, vector GIS represent map features as digitised points, lines, and polygon areas.

Lines are defined by a sequence of digitised points, and polygonal areas by linking a series of lines forming their boundaries. A hierarchy of features and spatial relationships can thus be evaluated by using the topological relations among the point, line, and area features forming the mapped region.

The vector GIS approach is especially good at representing sharp and unambiguous boundaries between map features. So vector GIS are preferred for displaying geological, land ownership, and facilities maps with high cartographic fidelity. The raster-based GIS are more often used during resource assessment and modelling. This is because the raster data structure:

- is readily linked to most numerical modelling functions
- provides adequate resolution for the creation of interpretive maps that often involve ambiguous or gradational boundaries between map features
- offers a convenient interface to many geophysical and satellite data sources, and
- allows for the discrete areas to be identified as well as display continuously varying phenomena.

3.5 Development of Geoscientific Information Systems

By the late 1980's it had become apparent that the conventional GIS products, with their predominantly two-dimensional spatial viewpoint, could not entirely satisfy geological analysis requirements. In particular, detailed definition of subsurface conditions, rather than just portrayal of their areal extent of geological, hydrological, climate, or environmental features, required volumetric representation referenced to three orthogonal axes. Numerical modelling and assessment of subsurface conditions further required that these volumetric data be linked to three-dimensional data manipulation procedures. A number of research initiatives began to explore the possible extensions of conventional GIS to better serve the geoscience community.

As far as can be determined, it was German geoscientists who first used the term "geoscientific information system" to describe the new approach (Vinken, 1986; 1988a; 1992a; 1992b). Initially they favoured the term "digital geoscientific map series" because they believed the terms "information system" did not fully describe the complexities of geological data capture, systemisation, and dissemination (Vinken, 1986; 1988b). At about the same time, Dutch geoscientists were concerned with developing comprehensive computer-based data handling and modelling applications for oil and gas exploration, and created the terms "GeoScientific Information System" with the acronym "GSIS" to describe their applications (Ritsema *et al.*, 1988). Meanwhile, Raper (1989) and many British developers were referring to similar systems as "Geoscientific Mapping and Modelling Systems" with the acronym "GMMS".

Since about 1989, the term "GeoScientific Information System" and the acronym "GSIS" have become more frequently used to describe computer-based three-dimensional systems designed to handle the variety of data and analysis needs of the geoscience community (Turner, 1991a; Bonham-Carter, 1994). The terms "GeoScientific Information System" and "GSIS" appear preferable to the alternatives because they offer a parallel to the widely applied "Geographical Information System" and its well known acronym "GIS".

3.6 Capabilities of GeoScientific Information Systems

The need for the acronym GSIS has been questioned, not least because many consider such geoscientific information systems as providing nothing more than support for standard GIS functions in a three-dimensional context. Some critics prefer to use the term "3D GIS". Yet the GSIS concept includes much more than just support for a three-dimensional geometry. When attempting to define, model, or visualize subsurface conditions, the geoscientist is usually faced with extremely sparse data, considerable complexity in subsurface conditions, and various types of discontinuities. Thus additional capabilities and functions must be provided within GSIS in order to fully support subsurface characterisation.

In general, GSIS must include:

- rapid and complex data interpolation and extrapolation procedures
- provide for interactive data manipulation, and
- support rapid visualization.

They must also support the range of distinctive data formats commonly encountered within a project, and should provide ways to illustrate the uncertainty inherent in the modelling process. No entirely satisfactory GSIS products yet exist that meet all these criteria.

3.7 Advances in hardware and software technology

The transition from two-dimensional GIS to truly three-dimensional GSIS demands considerable increase in the complexity of the underlying data management, analysis, and display functions. The level of computational effort as one moves from GIS to GSIS does not increase linearly, say from "2x" to "3x", but more or less exponentially, or by an order of magnitude, from say "x^2" to "x^3". Thus, although many scientists recognized the concepts and functions of GSIS in the mid 1980's, a practical GSIS implementation had to wait the arrival of sufficiently powerful and affordable computer hardware.

The late 1980's saw several technological breakthroughs in computer technology that resulted in the production of a new class of high-performance graphical workstations. These workstations crossed a critical price-performance threshold.

They provided graphical displays and numerical computation speeds that could, for the first time, support the three-dimensional subsurface characterization and modelling requirements required by the GSIS concept. Although the costs of these early graphical workstations were still quite high, petroleum company research laboratories and some government and university research facilities were able to procure limited numbers of these machines to undertake GSIS research and development.

While the past decade has shown dramatic improvements in hardware, corresponding improvements have not occurred in GSIS software. All the major commercial GSIS products can trace their early development to the period in the late 1980's when the high-performance graphical workstations first became available. Since that time the various systems have matured, and in many cases have added desirable features. But their fundamental architecture has not evolved. For instance, they do not fully reflect the structures facilitated by current computer systems engineering. This results from economic realities – the geoscience market has not been able to grow sufficiently to be able compete with other application fields for the attention of the programming teams. The current commercial GSIS products are able to perform the necessary analysis functions, but they remain expensive and somewhat difficult to use, not least because their user interfaces appear outdated and data transfer is somewhat difficult.

In contrast, a number of commercial GIS products, which are supported by strong user demands from a variety of fields, are rapidly evolving into "mainsteam" corporate, or "enterprise-wide", data management tools. Their costs have dropped while their analytical capabilities have greatly increased. It is now feasible, for instance, to undertake complex GIS analysis for a large project using relatively "standard" desktop personal computers. As these capabilities become integrated within corporate data management paradigms, the use of GIS can be expected to continue to grow.

The situation for GSIS appears favourable for re-development of the software systems in a somewhat similar fashion to those observed for recent GIS developments. The future expansion of GSIS applications will depend on improvement of their user interfaces, increased integration with modern data base concepts, reduced software costs, and the ability to rapidly and easily exchange and disseminate 3D data structures. The long-term role of the Internet in the data exchange and dissemination of 3D subsurface data seems assured. Current capabilities are not entirely satisfactory, but several research projects are addressing this requirement.

3.8 Classes of Geoscientific Information System

Three-dimensional GSIS technologies, although less mature than their two-dimensional GIS counterparts, may also be divided into two major classes on the basis of their method for defining spatial volumes (Figure 3.1). Volume representation methods are the three-dimensional equivalent of the two-dimensional raster; they divide the volume into discrete "volume elements", or "voxels". Surface rep-

resentation methods provide the three-dimensional equivalent of the vector-based GIS.

The majority of GSIS available commercially utilize voxels. Voxel methods offer a data structure upon which more specialized applications can be built fairly rapidly. They thus offer commercial advantages. In addition, voxel techniques are extensively used in medical imaging, they provide opportunities for displaying continuously varying phenomena, and they are more easily related to the grid-based structure used by many numerical models of physical systems. However, voxel representations can require very large amounts of data storage. For example, a volume represented by 100 rows by 100 columns by 100 layers requires 1,000,000 voxels, and yet only provides a relatively low-resolution image. In practice, volumes represented by tens or hundreds of millions of cells are more likely to be desired.

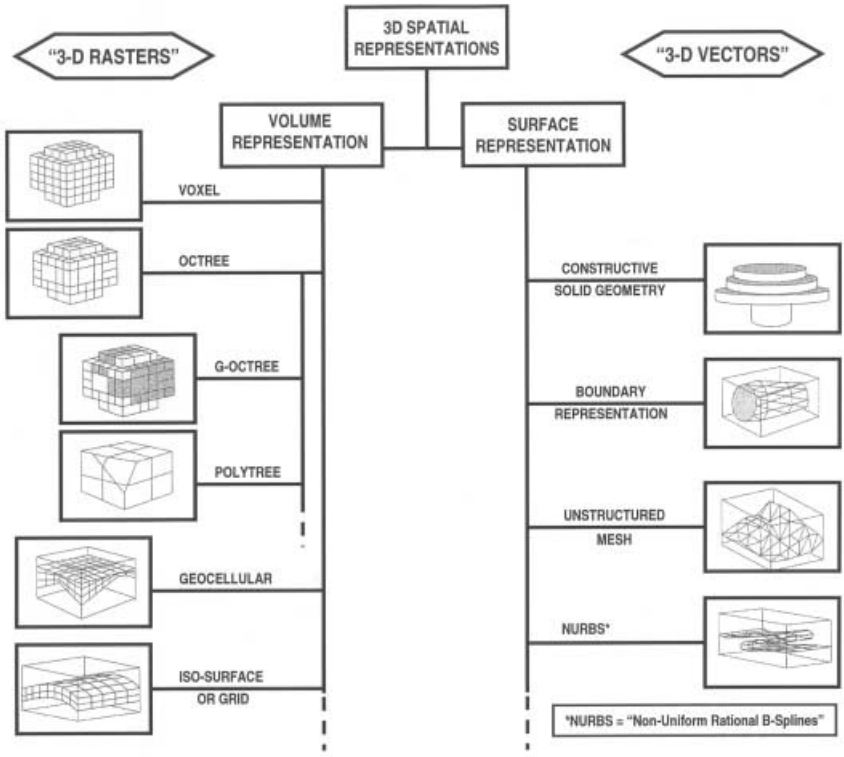

Figure 3.1. Three-Dimensional Spatial Representations

Medical imaging applications commonly use data compression techniques involving octrees and their derivatives (Gargantini, 1991). Such methods have not proved as successful for geological applications; only a few applications have been reported (Kavouras, 1987; Bak and Mill, 1989; Samet, 1989; 1990a; 1990b).

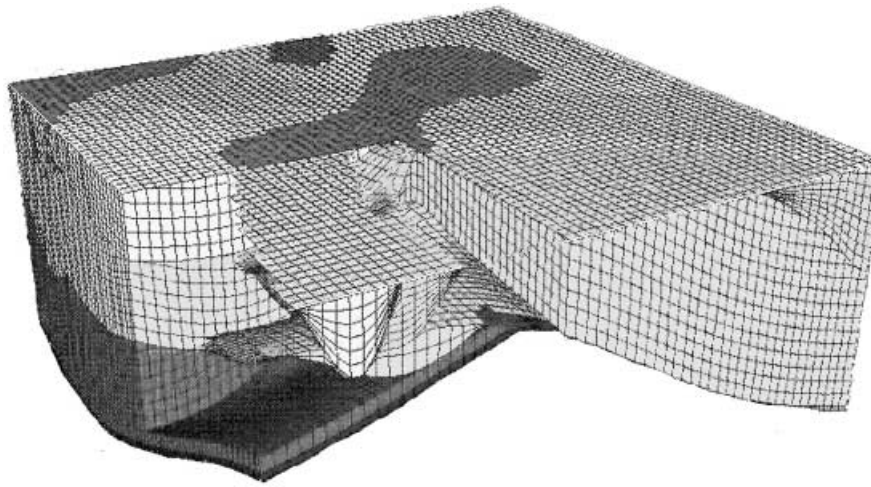

Figure 3.2. A Geocellular model showing multiple stratigraphic objects

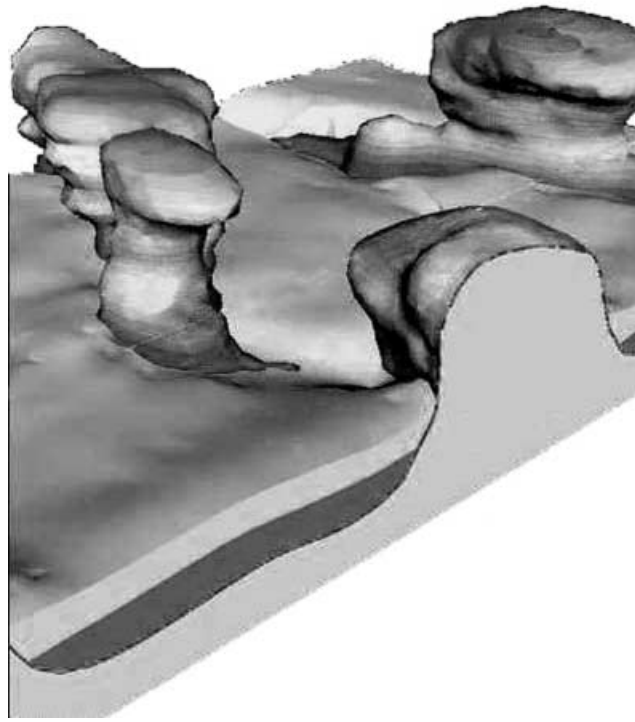

Figure 3.3. Salt diapir (with tone-filled elevation contours) simulation with sand layers [Image courtesy of Dynamic Graphics, Inc.]

Because many geological features are relatively thin and widespread, they are more continuous in the horizontal (x- and y-axis) directions, and show much more variability in the vertical (z-axis) direction. Some commercial GSIS products (e.g. Stratamodel) reflect this characteristic by allowing partially deformable "geocellular" voxels (Denver and Phillips, 1990). These have uniform dimensions in the x- and y-directions and variable dimensions in the z-direction (Figure 3.2). Other commercial GSIS products (e.g. EarthVision) convert a voxel data structure into a three-dimensional isosurface prior to display, as illustrated in Figure 3.3 (Smith and Paradis, 1989; Belcher and Paradis, 1991).

Surface representation methods have been less widely used in commercial GSIS. They involve a variety of techniques that are the equivalent of two-dimensional vector GIS methods. Constructive solid geometry methods allow the development of complex shapes by combining simple geometrical primitives, including cylinders, cones, and parallelepipeds (Bak and Mill, 1989; Kavouras, 1991). These methods are often used to describe man-made features, such as excavations, but are not suitable for representing naturally occurring geological features (Houlding, 1994).

Boundary representation methods include relatively simple polygon meshes and piecewise linear interpolations to define surfaces and geological features (Mallet, 1988; 1991; Houlding, 1991). These systems are frequently employed in commercial GSIS products used for mining applications (Houlding, 1994, 2000).

More recently, some systems have utilized unstructured meshes, the three-dimensional equivalent of the triangulated irregular network method (commonly referred to as "TIN") used by vector GIS. Unstructured meshes may involve a variety of fundamental elements, including tetrahedrons, hexahedrons, and dodecahedrons, and differ from the simpler structured meshes (such as voxel systems) in that they are not constrained by having to have a constant node and face structure (Gable *et al.*, 1996). This provides added flexibility during the development phase for a model that reflects subsurface conditions, but this flexibility comes at a price: added computational demands and very slow model construction unless sophisticated "mesh builder" software is developed and employed. Unstructured meshes also have the advantage of being able to link with finite element models. For these and other reasons, a number of research teams have invested considerable effort in developing unstructured 3D mesh systems, and "mesh builders".

Fisher and Wales (1990; 1992), Kelk and Challen (1992), and Lasseter (1992) have described experimental applications of curved surface and solid modelling based on advanced mathematical spline functions. For technical reasons, the most appropriate of these spline-fitting approaches appears to be the "Non-Uniform Rationale B-Spline", or "NURBS" (Figure 3.5).

3.9 Towards a desirable 3D data structure

Data management, correlation, and integration form the basis for geological characterisation. A variety of data types, data structures, and data management func-

tionality are necessary for efficient 3D, qualitative, quantitative, and visual representation of the geological subsurface.

Geoscience data types include characteristics (lithology, mineralogy, classifiers and codes), variables (concentration, grade, contaminants and properties), and 3D co-ordinates. Co-ordinates can reflect a variety of location systems ranging from global, such as Universal Transverse Mercator (UTM), to regional orthogonal systems containing northing, easting, and elevation values (NEL), or even the XYZ values of a local system. Efficient organization of large amounts of data is vital to a successful subsurface characterisation. Therefore, efficient data management issues must be addressed.

Houlding (1994) suggests that 3D subsurface characterisation requires four data structures: hole data, map data, volume data, and 3D grid data. Each of these data structures employs a different 3D geometrical definition.

Hole and map data structures provide vehicles for managing information derived from site investigation. For many projects, the majority of information is accumulated using boreholes. The identifiers for a borehole data structure would include borehole name, region, and description of the type of borehole data.

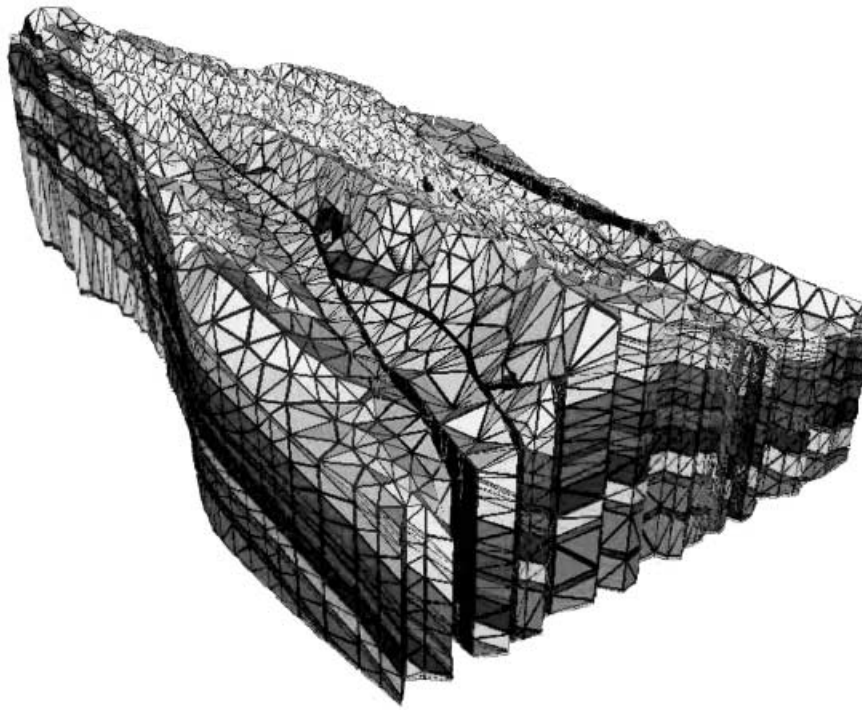

Figure 3.4. An unstructured 3D mesh system to portray an alluvial sequence

Figure 3.5. 3D NURBS model of two alluvial channels buried in South Platte River sediments. The channels were interpreted from cross-sections (shown as lines on surfaces in image). Cross sections were developed from borings (Turner, 1991b)

The geometry and locators of the borehole data structure include interval distance, collar or starting elevation/co-ordinates and survey records. Furthermore, the characteristic data source would include lithological and mineralogical intersections, rock properties and, if available, borehole geophysics traces.

Map data structures can similarly be identified, starting with a map name and description. The map data locators would be the co-ordinates defining the map's origin, and the azimuth and dip of its plane. The geometry of features would be portrayed as points, lines and polygons. Geological maps, cross-sections, site plans and surveys, contours, point samples, and surface geophysics would be common data sources.

Surface and volume data structures are used to interpret and predict structural and stratigraphic conditions, and for representing geotechnical engineering design information. Triangulated meshes utilising the TIN structure can efficiently represent surfaces. In layered sedimentary structures, a volume model can be readily derived from surfaces.

The component geometry of a 3D model is obtained by subtracting the lower TIN elevation values from the upper TIN elevation values. In more complex geological structures the volume geometry is more easily constructed using closed polygonal boundaries. One method uses three parallel planes – a mid-plane and two parallel planes on either side of the mid-plane. These outer planes are referred to as the fore-plane and back-plane. Connecting these planes by straight lines linking the corresponding points in each plane creates a volume using boundary representation methods.

A 3D-grid data structure allows prediction of continuous measures of spatial variation. Values for the desired variable are calculated and attributed to the centre

of each grid cell. The 3D-grid data structure representation has an origin, orientation, and dimensions.

3.10 The geological characterisation process

The various GSIS products approach the geological characterisation process in somewhat different ways. These differences largely reflect the typical geological environments that each system was developed for – some were developed for sedimentary environments while others were developed for hard-rock minerals extraction. In spite of such differences in approach, the geological characterisation process can be broken down into the following steps (Houlding, 1994):

1. Data management and integration of acquired information for a particular study area. Spatial correlation of data is an integral part of this step.
2. Data validation in terms of quality control and evaluation. Evaluation of the data allows determination of the the size and complexity of the project.
3. Interpretation of geological parameters. From the available data, the geological structure and stratigraphy of the area needs to be interpreted in order to properly characterize the subsurface.
4. Prediction of spatial variability of variables or properties. Spatial prediction techniques, such as Inverse Distance Squared or Kriging (Houlding, 1994; 2000), may be applied to the various sample values to estimate the spatial variation. Along with these spatial predictions, information can be obtained concerning the uncertainties of the variable distributions.
5. With the data created from the interpretation and prediction processes (steps 3 and 4 above), a final evaluation may be made and the subsurface characterization model then used to undertake evaluations of the study area.

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4 New paradigms for geoscience information management

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4.1 Introduction

Over the past two decades, geoscientists increasingly have been engaged in providing answers to complex environmental problems that have significant societal, political, and economic consequences. Today's geoscientific community faces greater public, governmental, and regulatory accountability. Clearly, a new information management (IM) paradigm must be established to better meet client and stakeholder needs. The systems used to store and generate geoscientific data must be re-engineered to meet those needs.

In order to effectively respond to societal requirements, geoscientists are now faced with the challenge of cost effectively collecting, managing, analysing, and synthesising multidisciplinary complex information. This data must be processed and disseminated in such a way that allows the public to make informed and rational decisions.

This paper addresses the challenges and the implications for geosciences information management in the 21st century. It concludes with a case study for a successful implementation of the new paradigms in an Environmental Restoration Project at the Los Alamos National Laboratory (LANL) by the Department of Energy (DOE). The project saw a need to upgrade and re-engineer its data and business processes to more adequately address client, user, and stakeholder issues of data accessibility, control, and quality.

4.2 Challenges facing the geoscience community

Risk management decisions have significant potential environmental, political, and economic consequences. These decisions are reached using large sets of multidisciplinary data that require timely and thorough reporting. In this situation, the geoscientific community faces specific challenges as it learns how to function under the following conditions.

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First, environmental work involves extensive and expensive work processes that must follow numerous federal, state, and local regulations. Stakeholders may not understand or accept highly technical explanations for remediation methodologies or procedures, yet all of these must be well documented. Addressing multiple-decision scenarios requires additional time and expense. All these situations frustrate geoscientists who typically are more interested in conducting good scientific work than in creating paper trails.

Second, effective tools for disseminating complex scientific concepts are not always available to the geoscientific community, or the community is not always familiar with those tools that are available. If highly technical information is not presented well to a non-technical audience, the non-technical stakeholder may interpret the presentation as a cover-up, an attempt to hide greater problems than actually exist. The response may be a demand for more sampling and data-gathering that does not clarify technical conditions but does increase costs (and frustration levels!) for the public and geoscientists alike.

Finally, most geoscientists are not involved in the legal aspects of defending data and remediation decisions. Consequently, they may not generate an audit trail that would allow rebuilding or defending such decisions.

Issues of compatibility and integration of work processes and technologies also challenge the geoscientific community. At a corporate level, poor communication and information exchange between corporate groups results in redundant activities and conflicting results. For example, when different organisational units conduct the same analyses without knowing of each other's activities, the result is duplicate analytical effort; multiple storage, format and locations (e.g. spreadsheets and desktop databases) instead of a common data warehouse; and unwanted cost. In addition, inconsistent operating procedures and the use of different and/or incompatible equipment and software creates a difficult environment for integrating data and interpreting results.

At the group level, daily tasks are impacted if highly specialised applications (i.e. customised to the group's internal work processes) limit effective communication and information exchange between units. Updating information and establishing and documenting audit trails becomes time-consuming, expensive, and difficult.

At the corporate level, complimentary supporting studies often are not conducted interactively because inconsistent processes impose technically difficult burdens on the personnel. For example, inconsistent data collection, data analysis, and quality assessment methodologies can make comparing similar data very difficult, and unnecessarily increases the risk of incorrectly interpreting results. This situation hinders the integration of multidisciplinary work groups into an effective decision-making process.

Understandably, such situations are less than optimal in the light of recent stakeholder and economic demands. This is because they make group-level deliveries unacceptably high in terms of time, cost, and quality. The lack of formal processes for data control and data quality, software standards, and protocols can threaten an organisation's credibility and weaken defensibility of results and decision-making.

4.3 The need for new paradigms

Clients and stakeholders have specific environmental and societal concerns. They want cost-effective answers to their questions, real-time access to data and an audit trail that ensures sound data control and data quality procedures have been followed (D'Agnese and O'Brien, *this volume*). To meet these concerns, the geoscientific community must shift to a new geoscientific Information Management (IM) paradigm that examines and realigns organisations, co-ordinates and formalises work processes, and integrates technologies. These efforts must support real-time data access and ensure that data control and data quality processes are established.

4.3.1 The challenge

Typically, organisations provide a range of services and products to meet the demands of customers and stakeholders. Successful corporations can be characterised as organisations of people that use a set of work processes and technologies with the goal of satisfying the customer inside a specific financial perspective (Figure 4.1). Customers want products that meet their time, cost, and quality needs.

An organisation's challenge is to align itself (i.e. create a pragmatic collection of *people*) so as to integrate practical work processes (i.e. re-engineer existing work *processes*), using appropriate *technology* (such as an enterprise system) to ensure that quality products are delivered on time at competitive costs. This people-processes-technology relationship is discussed further below.

4.3.2 Organisational alignment to meet stakeholder/client needs

Traditionally, most organisations within the geoscientific community are well suited to function at the unit level. For example, a typical geoscientific organisation might include a geology group, a hydrogeology group, and a geochemistry group. These people, processes, and technologies focus their expertise to meet the goals of a specific group, which often is driven by research and development (R&D). Their focus is science, not risk-management decision-making. They may be organisationally unsuited to providing the kind of risk-management decisions today's stakeholders and clients expect.

However, a client may need only a cursory understanding of the geology, hydrogeology, or geochemical inventory of a site. In today's world, the client or stakeholder may be more interested in environmental liability and in supporting risk-reduction than in the R&D aspects of an environmental problem. In this case, there is an obvious gap between the organisation's goals (fact-gathering and -processing in an R&D setting) and the client's expectations (decision-support information).

Therefore, closing this gap and providing satisfactory solutions for the stakeholders and clients becomes a priority. A shift is needed to a customer-centred

work mode that focuses on generating comprehensive results, multiple R&D groups, and translating the results into a language that stakeholders understand.

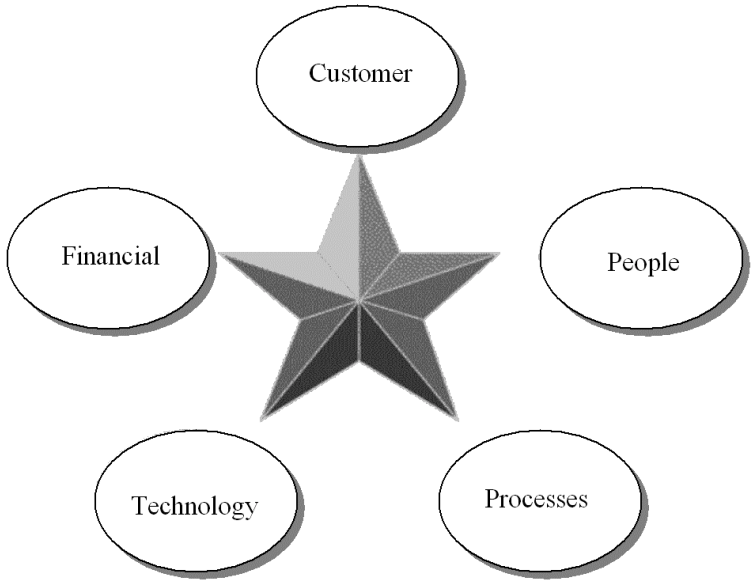

Figure 4.1. Paradigm of a '*Pragmatic and Practical*' organisation

4.3.3 Re-engineering the work process

Existing work processes can be re-engineered to meet stakeholder and client needs. According to D'Agnese and O'Brien (2002), today's geoscientists must learn to accept re-engineered processes and new technology that in turn will better meet customer requirements.

Re-engineering work processes are challenging, completely transforming the organisation's character. Re-engineering often replaces complex, tedious processes with simple, integrated work processes. Figure 4.2 shows a complex work process. Figure 4.3 shows a re-engineered work process.

Successful re-engineering focuses on developing specific metrics to ensure products will meet the customer's quality, cost, and schedule requirements (Darnton and Darnton, 1997). Organisations tend to behave according to established metrics. For example, if the metric is to produce 1000 lines of computer programming code a day, most employees will focus on producing computer code quickly rather than producing quality computer programs. The corporation, in this case, risks producing low-quality products that may meet the customer's schedule and cost requirements but are most unlikely to meet quality needs. If the metric is to produce "bug-free" computer programs, most employees will focus on producing quality computer programs with less attention being paid to production sched-

ule and cost. The corporation, in this case, risks producing high-quality computer programs that may not meet the customer's schedule or cost requirements.

During the re-engineering process, organisations must establish their goals (metrics) with respect their customer's requirements. Technology adds value to an organisation when it tracks and monitors those metrics to support continued enhancement of work processes (Information Delivery Incorporated, 2002). That is, if the stakeholder is interested in quality data, metrics must be created for applicable work processes, data control, and data quality.

4.3.4 An implementation strategy

To create a successful new IM paradigm, organisations must evaluate their existing processes and develop a solid implementation strategy to realign current work models in the light of new stakeholder and client demands. Re-engineering efforts should incorporate new technologies as old processes change. The challenges can be summed up in the following ways.

- Work processes and their associated metrics must be defined before new technology is implemented
- New technology must be developed in accordance with corporate and regulatory requirements and needs
- The technology must be designed and implemented cost-effectively
- The technology must be understood and accepted by the organisation and its employees (users)
- The resultant product must satisfy the needs of stakeholder and clients.

If the new paradigm is to be an improvement, it needs to be recognised that cost-effectiveness is not synonymous with lowest price. Cost-effectiveness is a function of the quality and robustness of the current technology combined with organisational acceptance. For example, even the most robust system, delivered at a low price, may not be cost-effective if it is not used (or worse, is used inappropriately) because it is perceived as being "no good" or not capable of being fitted into the user's daily workflow. On the other hand, even if a system is developed at a reasonable cost and is accepted by the organisation, it may be not be cost-effective if it has high maintenance costs or long downtimes.

Commitment to a well-developed implementation plan is key to introducing new technologies that change work processes. A successful new plan considers many issues: financial limitations, human-resources, time constraints, development and implementation factors that address how to work in the old system while the new system is being built and, most importantly, cost-effective technologies based on customer needs.

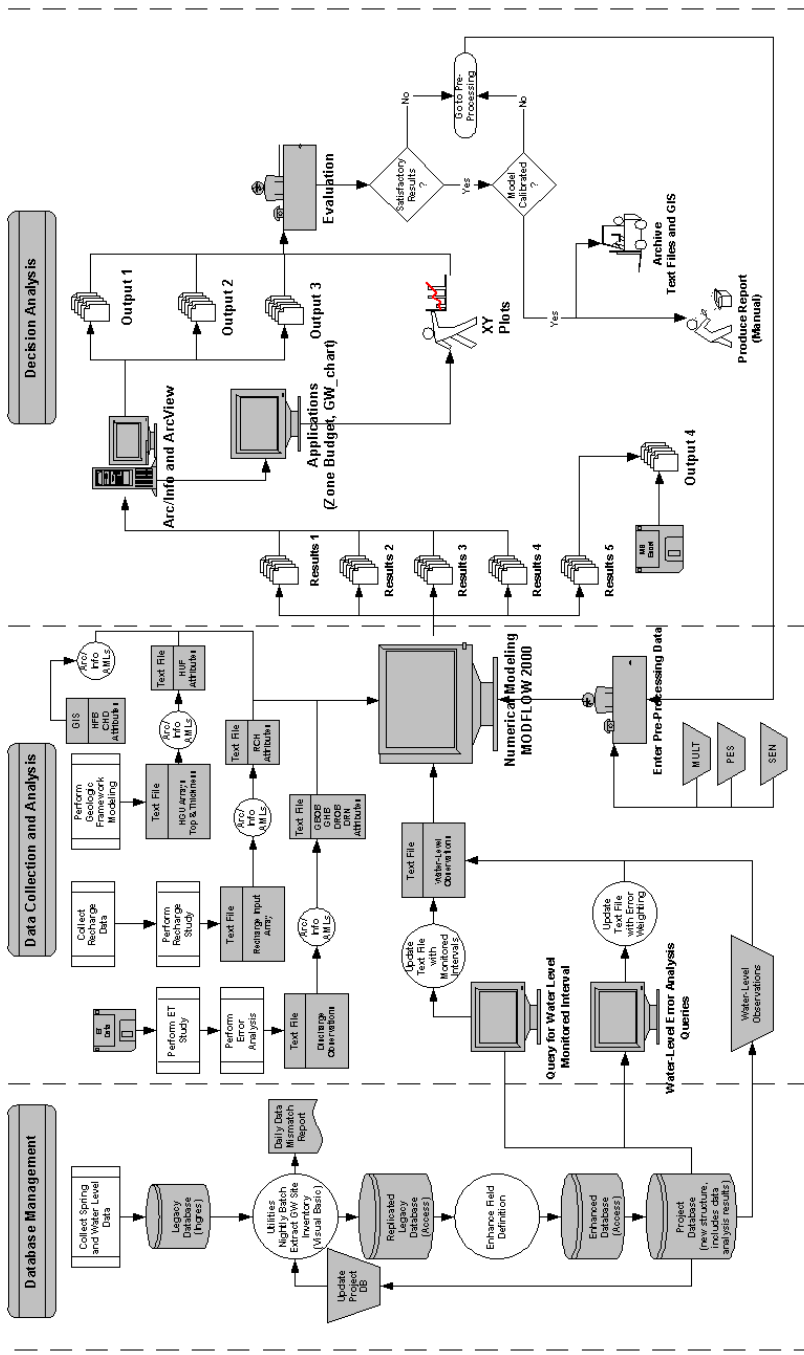

Figure 4.2. Example of an '*As-Is*' work process

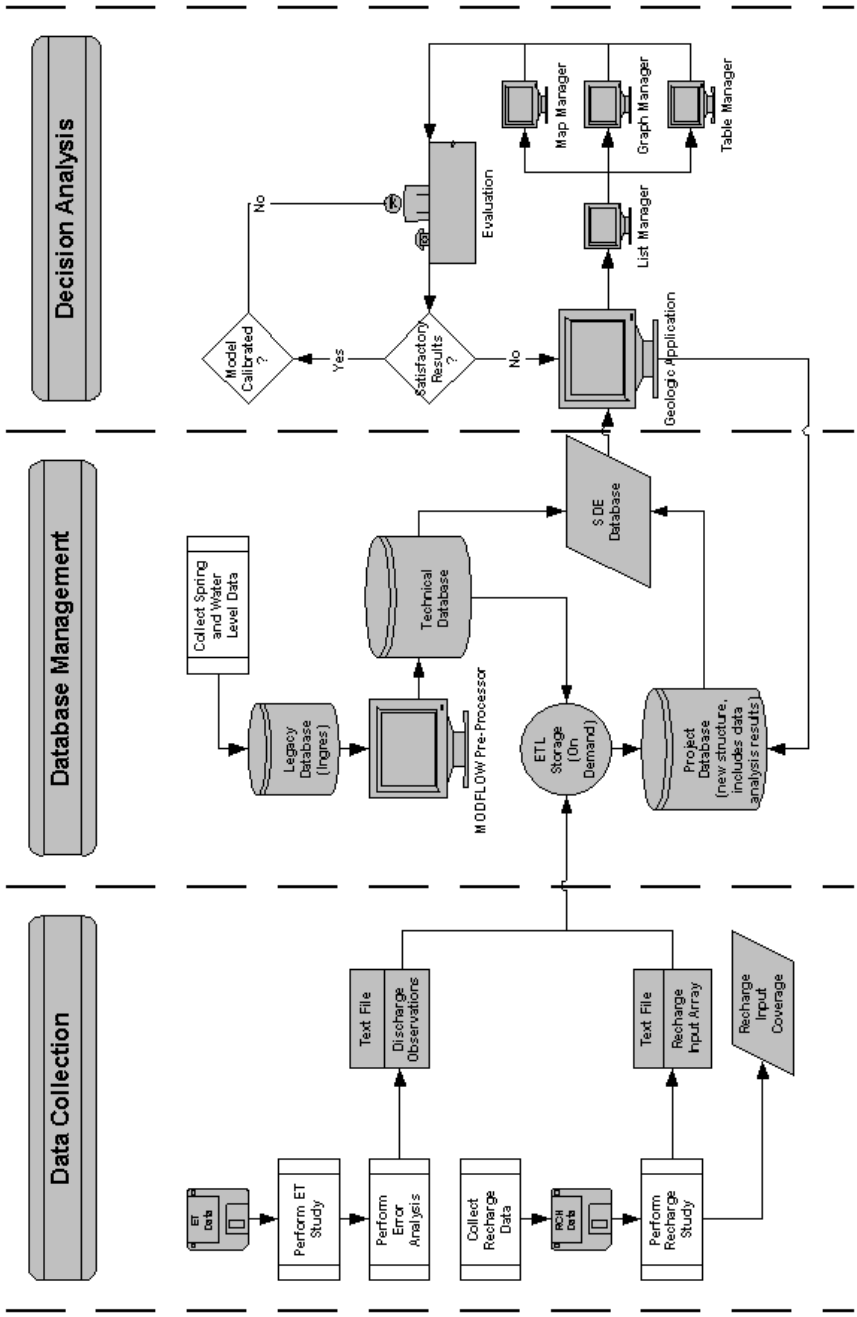

Figure 4.3. Example of a '*To-Be*' work process

The ER Project is responsible for the characterisation and clean up of 2124 potential release sites (PRS). These PRSs resulted predominantly from weapons R&D activities conducted since 1942. To meet ER Project goals and deliverables, the project conducts field-sampling activities to determine possible contaminants as well as the levels and geographic extent of contamination.

These sampling activities generate significant amounts of geological, hydrogeological, geochemical, and contaminant information. Ensuring accurate environmental appreciation, data quality review, analysis, and evaluation are integral to the project's business processes. A priority for project management was the creation of an infrastructure that would provide cost-effective data management and associated activities such as verification and validation. This infrastructure ultimately will support a defensible environmental administrative record that is generated and maintained with standard extraction, visualisation, reporting, and information-dissemination tools, and integrated robust tracking and control tools.

4.4.1 ER Project goals and needs

In addition to supporting the administrative record, ER Project management is committed to streamlining existing work processes that support quality environmental decision-analysis. One goal of this process improvement is to better meet the needs of the non-ER Project stakeholders with respect to the environmental decision issues facing LANL and surrounding communities. A second goal is to support the requirements and performance standards established by LANL, ER Project management, and state and federal regulators. Project management determined that improving decision analysis was dependent on improving three factors: data availability, data control, and data quality.

To accomplish these goals, management-level needs were assessed. Extensive interviewing identified a need for the following:

- a strategy to implement an IM system
- a qualified IM team to direct IM and re-engineering activities
- an effective IM infrastructure for information storage and retrieval
- formal processes to track information flow
- robust information audit trail processes
- more effective data-sharing with stakeholders.

4.4.2 Business process analysis

The next step in meeting improvement goals and fulfilling project needs was a business process analysis (BPA). A BPA consists of compiling an inventory and mapping existing work processes and data flow throughout an organisation. It identifies the people (roles and responsibilities), data, processes (how data moves through the organisation), and tools (manual and automated) that allow an organisation to perform its work. The BPA identifies gaps, inefficiencies, and current

misalignment with stated goals. The BPA then presents opportunities for re-engineering these existing work processes.

The ER Project BPA determined that the following factors prevented the organisation from fully realising its goals.

- *People*
  - Data quality and control functions were spread throughout the organisation, making effective management difficult.
  - There was no centralised IM leadership.
- *Data*
  - Data were scattered across the organisation in multiple, sometimes incompatible, formats. Little technical, regulatory, global indexing system (GIS) and management data were integrated.
  - Collection and reporting standards were not always followed.
  - The data-collection process, from initial generation to final deposit in a document repository, needed improvement.
  - Better documentation of data quality and integrity was needed.
- *Processes*
  - Sample management processes were inefficient.
  - Data management processes were not integrated with other work processes.
  - Document management processes were not integrated with sample and data management processes.
- *Tools*
  - Current tools for data management activities were insufficient and did not effectively support each other.

4.4.3 Success factors

An IM team assessed the results of the BPA and extracted several critical success factors. While some factors may be more important than others, typically all are necessary for a successful outcome. The project had to address the following:

- development of a management system plan
- creation of an IM technical team
- re-engineering of business processes
- hardware/software infrastructure implementation
- conceptual design development
- database design and GIS integration
- data migration and cleanup
- software definition (what the software will do) and development.

4.4.4 Strategic plan development

The next step was to develop an IM plan that addressed the needs and goals of the project, stakeholders and regulators. The critical factors dictated the sequence of events that needed to be accomplished.

Other issues, described below, also had to be integrated. For example, the plan had to create a robust data repository that could easily accept information, from initial sample collection to final reporting. The repository had to hold not only standard data such as geochemical results, document links, photographs, borehole logs, and the like, but also provide management with tracking information. Data needs to be added to the repository in a timely manner, for instance by allowing time for data quality reviews and facilitating responses to requests from the regulator for corrective action.

Work processes had to be refined to ensure that analytical data from the laboratories reported in hard copy form was consistent with the electronic versions provided to the sample management group. Standard, user-friendly data-extraction tools were needed so that the data could be published. The new system had to capture documented data integrity in order to preserve the quality of the data sufficient to support decision analysis. Complete document control was needed to support the decision-making process.

An IM strategic plan was developed and integrated into the overall ER Project strategic plan (Canepa, 1999), which was reviewed and approved by ER Project management and DOE. Their support was critical, because large-scale re-engineering efforts rarely succeed unless there is strong management support and commitment.

The IM strategic plan was developed using a phased approach; the new system had to work before the old system could be discarded. System components, new processes, and new roles and responsibilities were phased in so as to have a positive impact on the existing production processes. The team identified the following factors within the strategic plan as being critical to its success: the creation of an IM technical team, the re-engineering work processes, the infrastructure design and its implementation, the development of the conceptual design, creating a technical architecture for the database, developing a plan to clean up archival (legacy) data, and developing new software applications.

4.4.5 Creating the IM team

IM resources were evaluated, an inventory develped, and centralised into a single team under a leadership that reported directly to the ER Project management. This team was responsible for developing and maintaining the IM system, meeting the project's technical and business requirements.

Once the ER Project management had approved the IM strategic plan, the ER project made the commitment to create a centralised IM system that would support the transition from the old processes to the new. Both systems were to be maintained until the new processes were established, tested, and demonstrated to be functioning robustly. A major reorganisation was initiated to ensure that all IM

groups were organised under one person and ensure that the mission was well-defined.

Before the re-engineering could be initiated, the decentralised IM structure needed to allow each functional group to maintain and control its own data. The decentralised structure made many IM functions redundant: development efforts were hindered, duplicate data had to be stored and maintained in numerous places, and staff skills and training could not be not co-ordinated. This structure made co-ordinating efforts difficult and prevented development of an integrated system that could meet user, stakeholder, and regulatory needs.

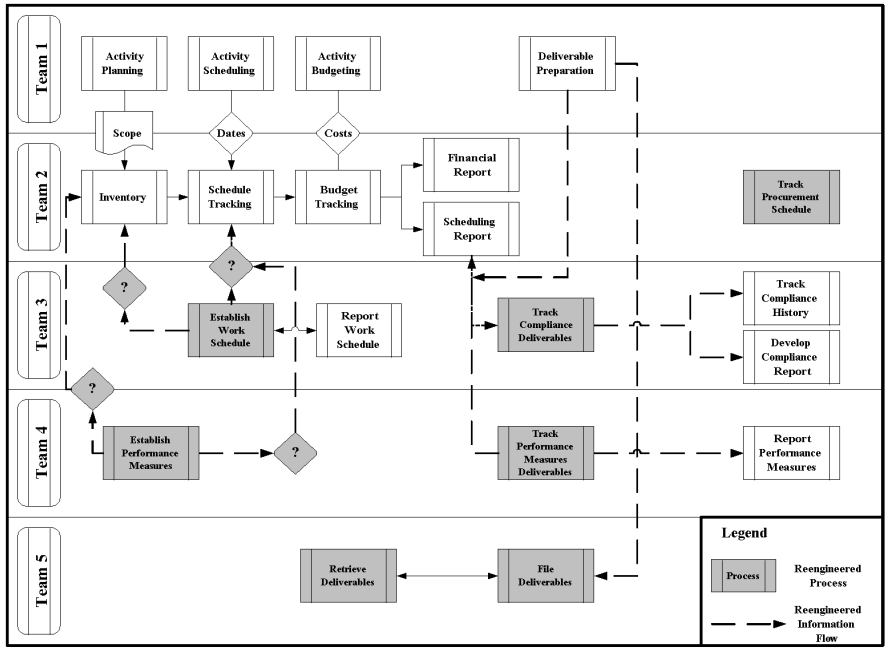

Figure 4.4. Example data flow diagram for a management business process.

4.4.6 Re-engineering the business processes

The ER Project work processes could be categorised as either technical processes or business processes. These processes were then duly identified, an inventory compiled, and priorities set in accordance with the project's strategic plan. The strategy for process re-engineering focused on those processes which were critical to the project's short-term mission and to the planned longer-term system components. Business processes were integrated throughout the development phase and standard operating procedures (SOPs) updated, guidelines prepared, and quality assurance procedures established (Figure 4.4).

4.4.7 Implementation of the hardware/software infrastructure

In order to more effectively meet stakeholder and ER Project needs, the IM strategic plan required the creation of an enterprise-wide system that allowed access to tools and data, and encouraged communication across the organisation. It also called forelimination of independent data holdings by individual groups and the use of incompatible technologies (Canepa, 1999). To achieve this, the hardware and software infrastructure had to be substantially upgraded and standardised.

The infrastructure consisted of multiple hardware platforms. These included both Macintosh and Windows-based desktop and laptop computers, and Unix-based workstations. Users ran various incompatible spreadsheets and database management systems, including 4D, Access, SQL Server, and Oracle, and employed both Microsoft Internet Explorer and Netscape browsers. The infrastructure was also characterised by multiple domains, data was stored on desktops but not captured by the project's main database. Some users did not follow standard business practices: there was inadequate backup of files and protection against fire and/or theft. In short, although everything worked on a daily basis, data accessibility was not optimal, development efforts were impaired, and data processes were not well-documented. The ER Project concluded that although the multiple platforms and the legacy of archival systems could be accommodated, the cost of integrating and maintaining these systems outweighed the cost of upgrading with the development of a single integrated system.

State-of-the-art technology was therefore implemented in order to create a single domain with a uniform, compatible hardware platform. Software options were standardised using centralised file and data servers. Daily backups that effected system redundancies were implemented so as to ensure reliable system operation.

4.4.8 Conceptual system design

Figure 4.5 shows a summary of the technical processes required to support the ER Project's goal of closing PRSs. The process automation application required for each of these work processes is also shown on this figure.

In order to support the automation of the re-engineered processes and workflows, a conceptual design for the IM management system was developed, as shown on Figure 4.6. This system consists of a central database repository to store point data in a Relational Database Management System (RDBMS); a Spatial Database Engine (SDE) is used to store the geological data.

A series of components were thus designed, falling into two categories:

- Data gathering applications
- Data visualisation and decision management tools.

Once the conceptual design had been approved, the data gathering applications, the central repository, and the enterprise applications could be put into place. Figure 4.7 shows the architecture and technologies that were used.

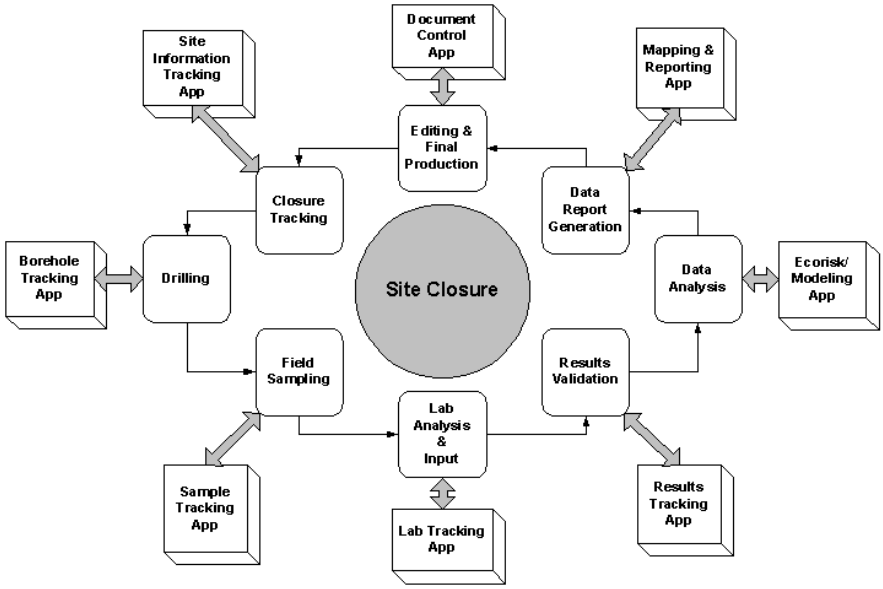

Figure 4.5. Work Process and Corresponding Automation Application

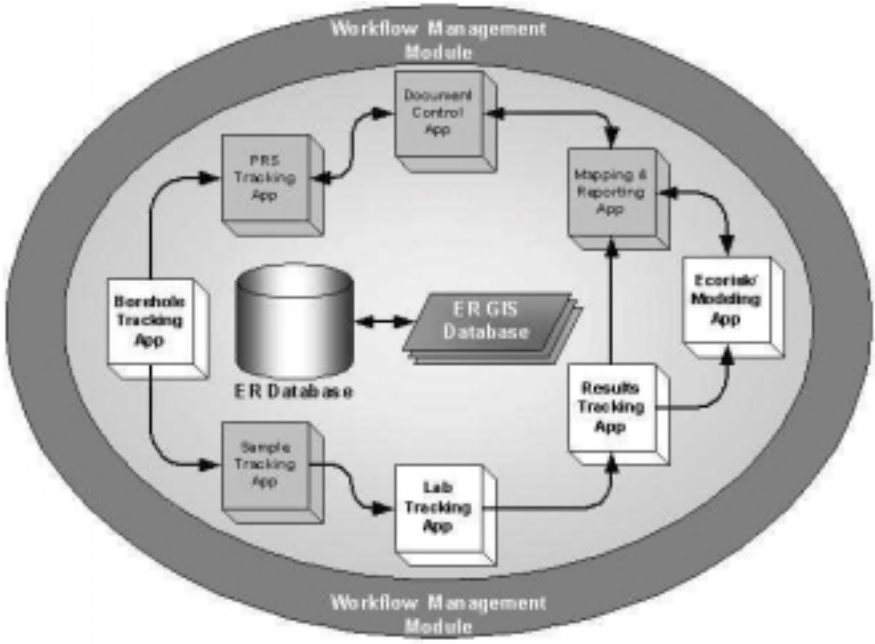

Figure 4.6. System Conceptual Design

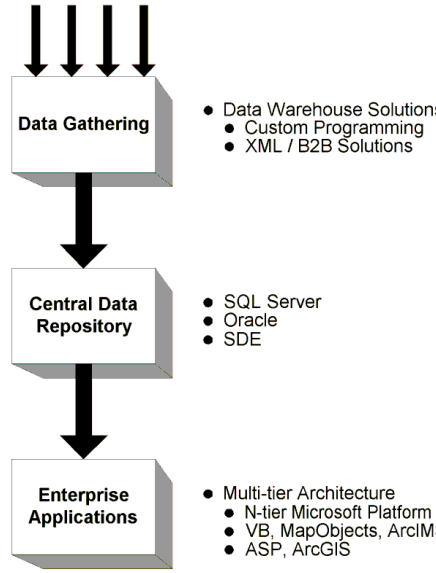

Figure 4.7. System Architecture and Technologies

4.4.9 Database design

The ER Project Database was designed to support all phases of the ER process, from start to end. It is a comprehensive design that allows the integration of workflow data and technical data within a single data store (the ERDB).

The workflow data comprises the ER project business data, management data, and business rules which support the ER workflow process. The technical data comprises field data, results and analytical data, as well as the geospatial information necessary for geoscientific analysis.

The database consists of 300 tables. These have complex relationships but with the potential to form a DOE environmental data management standard. Figure 4.8 shows the various database modules for the ER Project database.

4.4.10 Data migration and cleanup

Having deployed the ER database, the next step was to clean up the archival (legacy) data and transfer it to the new database structure. A significant amount of environmental data had been collected over many years, under a number of different regulators, and employing a variety of standards and methodologies. These data were stored in a wide variety of databases, and as hard copy. Data needed to move to the newly standardised structure and checked for accuracy, for instance against the hard copy. The data migration and cleanup included approximately 2.5 Million records of analytical data!

One would think that any two systems that maintained similar data would have been performing similar tasks. Thus information from one system should map to another with relative ease. However, this hardly ever happened in practise!

The archival systems proved to be far too lenient with respect to enforcing integrity at the elemental level of data. Fields that should have been populated from a list of valid values, such as *STATES*, tended to require that a specific value be entered, but these were seldom validated against the value intended by the user.

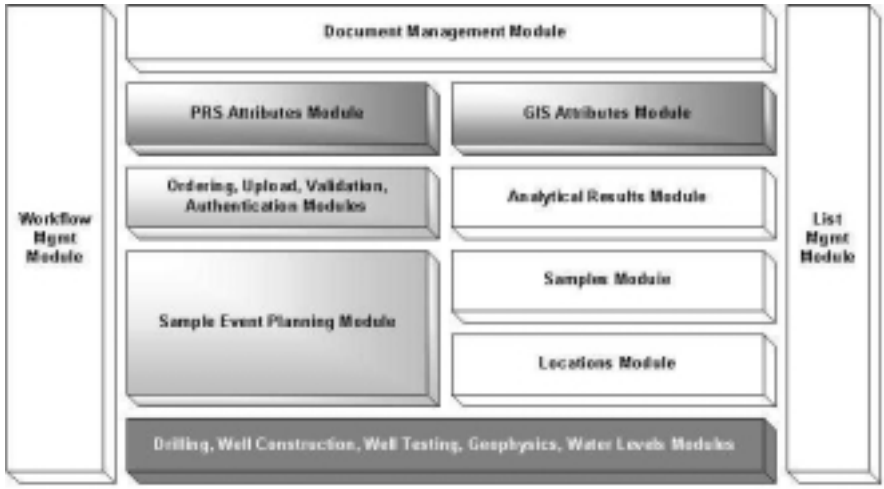

Figure 4.8. ER Project Database Modules

To prepare for and execute a successful data migration, it was recognised that data migration would need to comprise more than the simple act of transferring data from one system to another. Several questions had to be answered early on:

- Which were the source systems containing the archival data?
- What volume of data needed to migrate?
- How many interfaces would be involved?
- How much data cleansing would be required?

This involved examining the actual data that had to be transferred. The data transfer plan was broken down into several phases:

- Strategic Phase
- Analytical Phase
- Implementation Phase

The focus of the Strategic Phase was to determine the scope of the migration. In other words, answer the question, 'What we are trying to transfer?' This was the time to identify the number of archival systems requiring migration and establish their data structures. Interfaces are another critical factor that were identified at

this juncture. Interfaces are no different from other data sources, except they may receive data from the new system, as well as supply data.

At this point, the team was not only identifying the number of data files but also the number of different systems from which data were to be transferred. Data sources were not limited to actual data processing systems. Inevitably, employees were encountered that maintained files on their own workstations, used to accomplish specific tasks essentially for their own use.

The Analytical Phase was not intended to thoroughly identify the transformation rules by which historical data would be massaged into the new system; rather, it involved making a checklist of the archival data elements that had to be transferred. This list of data elements came from the following sources:

- Archival data analysis. Comprehensive data cleansing research was undertaken, extending the information into the Strategic Phase.
- Archival report audits. Archival reports from the old system were reviewed. A comprehensive list of field usage was thereby generated.
- User feedback sessions.

The Implementation phase is where the bulk of the actual mapping of archival data elements to columns took place. **Note:** Data migration is iterative – it cannot happen in a single sitting.

The mapping portion of a data migration project spanned the Analytical Phase across to the Implementation Phase. The reason for this is that the most important resources for validating the migration are the users of the new system. Unfortunately, they are unlikely to be able to grasp the comprehensiveness of the migration until they can view the data through the new applications.

Experience leads to the conclusion that developing the new reports prior to invoking the new forms permits a more thorough validation of the migration, earlier in the project. For instance, if some sort of calculation was performed incorrectly by a migration script, reports would reflect this. A form typically displays a single master record at a time, whereas reports can display several records on each page, making them a better means of displaying the results when testing the migration.

4.4.11 Software definition and development

A conceptual design for each software application was developed based on the reengineered work process. This generated the detailed requirements, leading to creation of a requirements document. The review process could then begin.

After a requirements document has been created, it could be brought under configuration control so as to take account of any changes to requirements that could impact on the budget and/or schedule. Coding, testing, "bug fixing", and tracking could then take place. However, even after the application had been put into production, the development process would not necessarily be complete as new enhancements and changes in requirements could occur. Adherence to a development process is therefore critical.

The software approach was to build an IM system based on an expandable framework (Figure 4.9). Applications such as LIST create lists that in turn create tables, graphs, and maps. This from the ERDB and spatial (ER Project GIS) databases, and is accessed only through the enterprise system. Instead of developing a monolithic application, the approach was to develop and deploy clearly defined software components that could be integrated easily into the overall system. These components fell into the following categories, the concept of the user applications being illustrated in Figure 4.9. These were identified as being user-critical during the requirement-generation and -review phases of the development cycle:

1) Data and Information Input Applications included:
    a. Sampling event planning applications
    b. Sample tracking applications
    c. Electronic Data Delivery and Data Checking applications
    d. Data Verification and Validation
    e. Data Quality Assessment

2) Data Reporting and Data Dissemination Application included:
    a. Data extraction and analysis applications
    b. Visualisation and mapping applications
    c. Decision management applications
    d. Web-based informal portal and reporting

3) Administration Applications included:
    a. Workflow Management
    b. Document Control System
    c. Database Administration Applications.

4.5 Conclusions and the Challenges Ahead

Today's geoscientists are faced with the need to create a new paradigm that meets client and stakeholder requirements, by creating systems suitable for storing and retrieving data. They must close the gap between organisational goals that focus on a fact-gathering or R&D process and the customer's expectations, which focus on the need for more and better information. Tools are needed to retrieve this information easily, and ensure timely delivery.

The LANL case study exemplifies successful implementation of the new IM paradigm. The ER Project successfully re-engineered its business processes while work was on-going. New work processes and electronic systems were built that better met their own needs and the needs of stakeholders. Readily accessible data, integrated data types, and improved data control and data quality not only satisfy user needs but also create audit tracking capabilities that can be used to defend management decisions. The IM paradigm thereby greatly reduces the risk of failure and increases stakeholder and client satisfaction.

Such an infrastructure, including the documentation processes, can thereby be successfully created provided an organisation is willing to support these processes, providing a launching pad to accelerate complex environmental decision support.

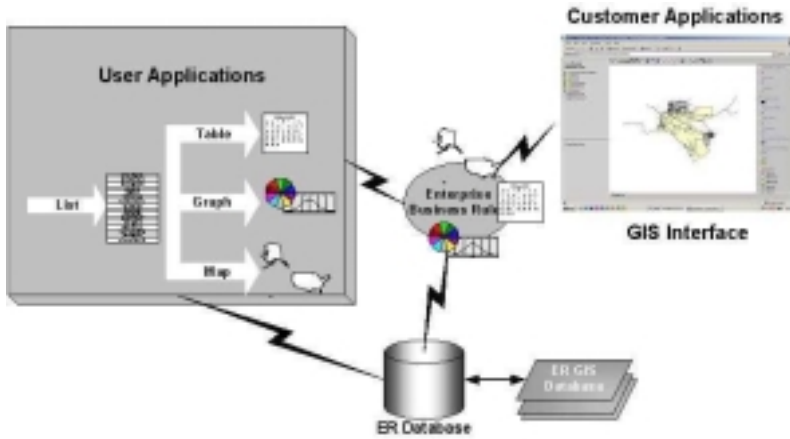

Figure 4.9. Concepts concerning user applications

The geoscience community at large is, however, still faced with many challenges towards shifting paradigms, including the following:

- Who defines our business processes?
- Who will freeze our system requirements (a management consultant, a geoscientist, or an IT professional)?
- Challenges in system architecture
- XML versus B2B for data gathering
- 2-tier versus n-tier architectures
- Thin- versus Thick-client applications
- Challenges in system design
- Relational- versus Object-oriented databases
- Business rule encapsulation and maintenance
- 3D application interfaces across the enterprise.

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Part B End-User Requirements

The urban underground environment is primarily concerned with the shallow subsurface. Most load-bearing structures and many infrastructure and utilities elements are located within 50 m of the ground surface. The complexity of this zone, frequently increased by anthropogenic disturbance, presents very difficult characterisation problems. Characterisation of the deeper subsurface is important for groundwater resource evaluations, environmental contamination assessments, and for some infrastructure applications such as underground storage facilities.

Engineering the shallow subsurface relies fundamentally upon suitable ground investigations that are based upon recently available information technologies, while also considering the associated social, economic, and policy issues. Many are familiar with large data collection efforts or information systems that failed, not because they were scientifically or technologically wanting, but because they just did not meet the needs of any significant user community.

The role of the geoscientist as an information provider (e.g. through the use of models) is changing. In geological modelling, the geoscientist, and the procedures and methods used, need to become increasingly customer focused. A parallel situation has emerged in geotechnical engineering, where some areas of research are focusing on the end use of a material or product. 'Performance based' testing is used to determine whether it is 'fit for purpose'. Similarly, geoscientists must focus increasingly on the 'end use' of their experience and knowledge. In geological modelling, the geoscientist, and the procedures and methods used, need to remain aware of what the user of the information requires.

The papers in Part B emphasise the dialogue between information providers and information users. They explore technological capabilities on the one hand and user needs on the other.

"Users want solutions, not data" and "Users want information they can use immediately in a form they can understand" are two fundamental assertions. The model should not be an end in itself, rather it should be the means to an end. These precepts perhaps explain why so many potential users of geoscientific information experience problems with what geoscientists produce. It appears reasonable to ask what indeed it is that geoscientists produce.

Users may not care particularly about the spatial or time dimensions within models. Geoscientists, as providers, need to look beyond their own specific interests and remember that the model is primarily a means for acquiring the information needed for the intended specified purpose. The societal demands for environmental care have special relevance, yet the economics of development do not encourage individual contractors or government agencies to fully consider the long-range effects. The lack of consistent documentation of ground-related features results in additional difficulties. Integrating the interests of science, industry and social sectors is clearly desirable from a holistic viewpoint, but is limited by lack of compatibility of data and documentation. There is now a need to define an

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appropriate data management paradigm that can permit flexible use within future, yet-to-be-defined contexts.

As Kaalberg *et al.* point out in Chapter 6, from the users point of view the best strategy for the acquisition of geological information should be guided by a value-based approach within the ground investigation phase. Further effort should then be expended on the acquisition of additional information only if that information can be expected to significantly enhance the control of the construction process in terms of safety and overall cost. Such an approach can be established by integrating ground investigation tools or indicators within the construction process. If used correctly, this can provide relevant information at the exact location of interest. However, such models or algorithms do not yet exist and thus now require development, to the extent that they are capable of processing ground information in real time and capable of being seamlessly incorporated within the construction process. Based on knowledge gained from experience, this could form the paradigm for geoscientists in the coming decade.

5 Putting the user first: implications for subsurface characterisation

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5.1 Introduction

Successful use of new information technologies to improve subsurface investigations depends on accurately identifying user requirements, and also the associated social, economic, and policy issues. Many are familiar with large data collection efforts or information systems that failed, not because they were scientifically or technologically wanting, but because they just did not meet the needs of any significant user community. This paper is based on experience gained in applying 3D modelling for subsurface characterisation over more than 10 years.

5.2 Defining user requirements

The problem may be expressed from the viewpoint of experience, which has shown that data alone are insufficient to most users. "Users want solutions, not data" and "Users want information they can use immediately in a form they can understand" are two fundamental truths. These truths explain why so many potential users of geoscientific information experience problems with what geoscientists produce. It would be reasonable to ask what indeed do geoscientists produce.

Both data and information are produced, as traditional products and as thematic products. The traditional products include geological maps and a variety of highly technical scientific reports. These products are designed for use by specialists. Traditional reports frequently employ extensive technical jargon that provides scientific precision but cannot be understood by the non-specialist. Geological maps are based on a very specialised graphical method of representing 3D spatial relationships on a 2D piece of paper. They accomplish this while employing 19th Century-printing technologies – a truly remarkable feat.

An increasingly wide variety of thematic products are being produced. These focus on a specific theme, or sometimes a market sector or particular type of user. Examples include reports on specific regions that emphasise the environmental conditions, historical aspects, or natural processes. Many are written in simple

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language and include carefully designed and colourful graphics that appeal to many readers. Thematic products are produced in a variety of media, including digital products such as videos, CD-ROMs, and Internet access pages.

5.3 The problem with traditional products

The problem with traditional products, specifically geological maps, is readily illustrated by a fairly recent example from the United Kingdom. In the early 1990's, the British housing insurance industry was facing catastrophic losses following a drought that caused clay soils to shrink and building foundations to crack. One underwriting group decided that geology might provide a guide to the scope of the problem and so purchased some standard geological maps from the British Geological Survey. Their reaction to these maps was that they represented "pretty colours and confusion" because they could not interpret them.

Subsequent interactions with the British Geological Survey resulted in the development of specific products targeted to the user (industry) requirements, but the process was not without some difficulties and took quite a long time.

Many, perhaps most, national geological surveys are faced with rapidly changing user requirements. When originally established a century or more ago, most geological surveys were expected to work with the mineral exploration industries to help provide the raw material resources required by the industrial revolution. Later, many of these surveys became responsible for assisting in the discovery of petroleum resources. Both of these activities required interactions and communications between geoscientists – some employed by the geological surveys, others serving on university faculties or employed by the exploration industries. Thus traditional products – geological maps and scientific reports – served the communication functions well, and both data and information were disseminated.

5.4 Developing new products to satisfy modern users

In contrast, the modern world has rapidly brought new demands and new users to the door of the geoscience data provider. The example of the British insurance industry described above clearly shows some of the resulting communication problems. Unlike the older resource industry based user community, the new users often cannot use basic geoscience data because they have no capability for interpreting it. In many cases they cannot evaluate the merits of alternative interpretations. When provided with a series of such alternatives, they become confused. They may also be unable to distinguish between theories and facts. In short these new users clearly reflect the two truths defined earlier – "solutions, not data" and "information in understandable form".

Users can be classified in terms of their information acceptance capabilities as "Thick" or "Thin" clients (Figure 5.1). A "Thick" client is one that can accept and interpret or evaluate a great deal of raw data. They desire a wide variety of data

and information, and hence accept a "wide," or varied, and very rich data/information stream. Hence they can be termed "Thick" clients. In contrast, the relatively unsophisticated user only desires a relatively simple, concise answer to his or her question. A small amount of carefully selected data or information usually suffices to meet their needs. Hence, such users can be defined as "Thin" clients. Figure 5.1 also shows another important phenomenon. The thin clients are very numerous – they represent the broad public – while the thick clients are much less numerous.

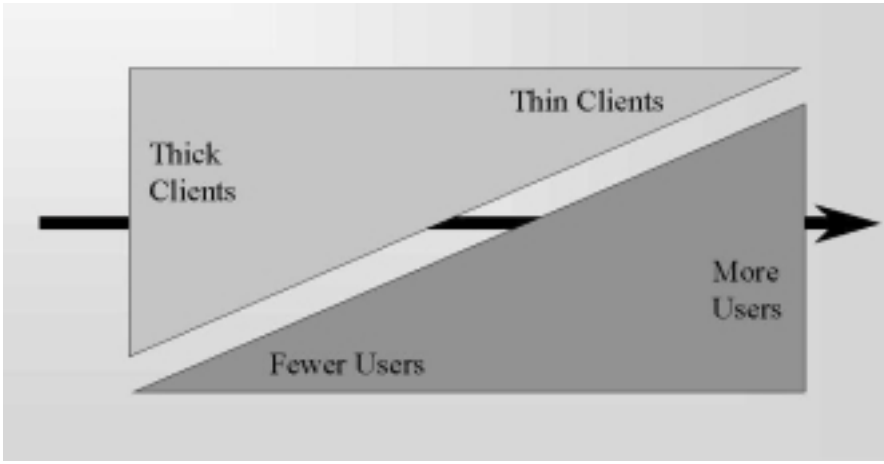

Figure 5.1. The concept of thick and thin clients

Unless information systems are developed to serve the needs of these thin clients, support for the entire geoscience discipline by the public will cease to exist. If geoscience is largely ignored by society as being unimportant, funding will rapidly disappear, and thus so will the ability to serve the specialist thick clients. Without the thick clients, scientific advancement will stop. So the importance of making sure that "the user is put first" when designing the subsurface characterisation tools is of paramount importance.

5.5 Geo-Objects and subsurface modelling

Kelk's description quoted in the introduction to Part A (*this volume*) refers to the concept of "Geo-Objects". What are "Geo-Objects" and what characteristics do they have that make subsurface characterisation and modelling so special? In short, why is it that geoscientists cannot just use CAD (Computer Aided Drafting) systems to model their subsurface features, just like engineers design and model complex man-made structures?

Various geological features or units that exist in the subsurface can be considered to form Geo-Objects. Raper (1989) introduced the concept of a "geo-object" and noted that there are two distinct types – "sampling-limited geo-objects" and

"definition-limited geo-objects". Features such as a rock layer or a fault plane, whose position in space can be better identified with additional samples, are termed "sampling-limited geo-objects". Ore shoots, sedimentary facies, or pollution plumes, which can only be visualised by first selecting a threshold parameter and level for inspection, are termed "definition-limited geo-objects".

Both types of Geo-Object usually exhibit the following characteristics:

- complex geometry and topology
- scale dependency, including hierarchical relationships
- fuzzy, property-ruled boundaries
- may contain holes and separations
- may be embedded in other objects
- display heterogeneity and anisotropy of properties

Thus geological modelling of the subsurface typically encounters geo-objects that have complex geometry and topology, and may have fuzzy definitions and scale dependencies as illustrated by the buried river channel sand shown in Figure 5.2. In contrast, most engineering design objects appear as in Figure 5.3. They are much more regular, homogenous, and well defined, and so can be designed with CAD tools.

Figure 5.2. A typical "Geo-Object"

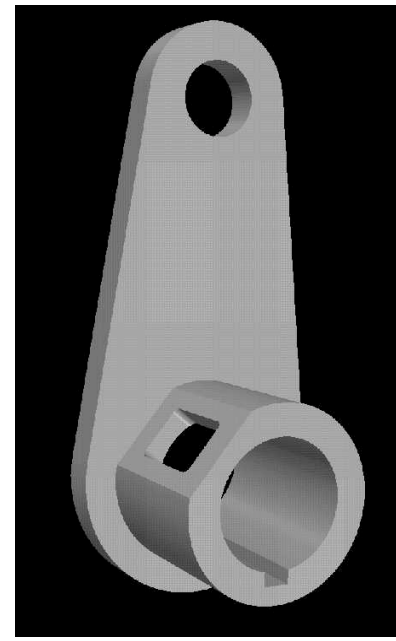

Figure 5.3. A typical engineering object

A critical 3D geological subsurface modelling problem is created by the lack of sufficient definitive data. Field observations, such as the boreholes shown in Figure 5.4, are usually very widely spaced. In order to build an acceptable model, the creator must interpolate between these widely spaced data points.

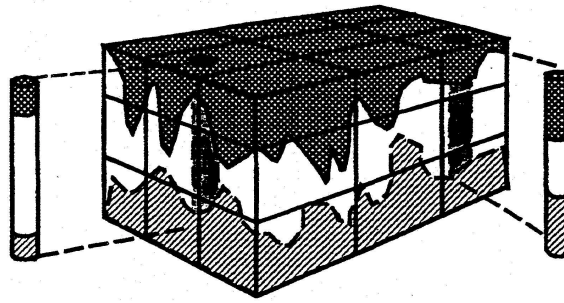

Figure 5.4. The fundamental model-building difficulty

5.6 Solutions to improve efficiency

How can increased efficiency in model construction be achieved? Several potential solutions are provided in this volume. Many individuals and groups are testing new approaches concerning how best to build 3D models from isolated observational data supplemented by secondary inferred data, such as provided by geophysical surveys. Specifically, how can scientists connect the known conditions at the sampled locations to form a 3D model without the expensive and time-consuming task of developing a series of digital 2D cross-sections? How can real-world complexity be modelled? How can the models be verified? How can the models represent uncertainties of the geological framework (i.e. the shapes, continuities and relationships of the geological features) and the physico-chemical properties within the units?

Several research approaches are under way to resolve these questions. The key appears to lie less with developing new GIS tools and more with methods that "discover" the necessary parameters which control the observed geological framework architectures by using existing field observations and data sources. What appears to be required is some way to harness the experience and understanding of the geoscientist in the model-creation process.

5.7 Implementing new information technology

Evolving information technology concepts are also providing tools critical to resolving the problems of subsurface characterisation. Historically GIS methods

have evolved in isolation from corporate data bases. As shown in Figure 5.5, a "firewall" was erected between the spatial analysis tools provided by GIS and the corporate-wide financial and operational data. Only a very thin "pipe" passes through the firewall to connect the two data bases.

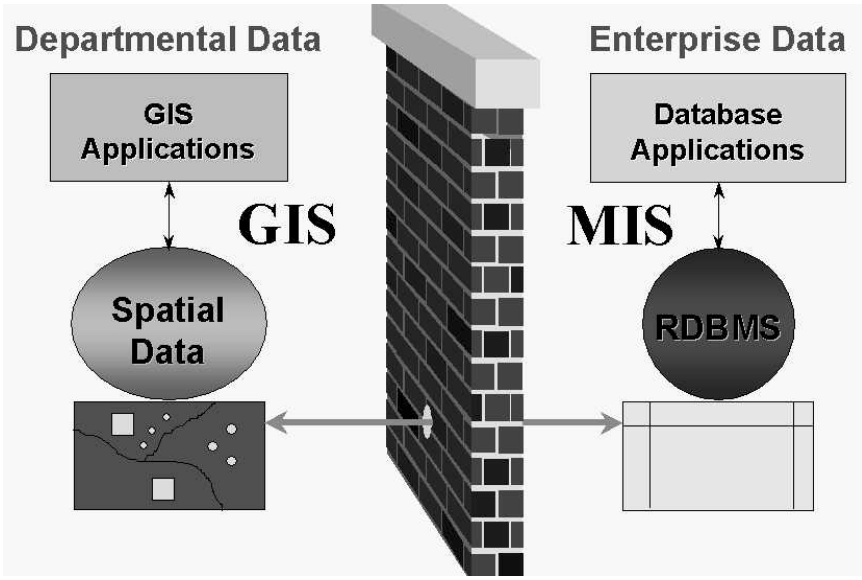

Figure 5.5. Historical view of GIS Technology

There were, of course, good reasons for such a practice. As GIS developed, the existing database technology could not support the long transaction times involved in editing and updating spatial data files. The financial and business transactions undertaken with the corporate data base involved much shorter time steps. Faced with this dichotomy, the solution was to keep separate the GIS data base. This made the operations feasible, but at the price of placing the GIS data away from the centre, and also of introducing a host of problems concerning maintaining data integrity between the two databases.

Fortunately, beginning in about 1995, the database and GIS technologies matured to the point that long transactions could be readily supported. Several vendors, including Oracle, began offering the ability to manage spatial data queries within traditional databases, while GIS vendors began to allow the use of multiple or dispersed databases by their products. There is thus now the opportunity to consider data management systems as illustrated by Figure 5.6 to support subsurface characterisation.

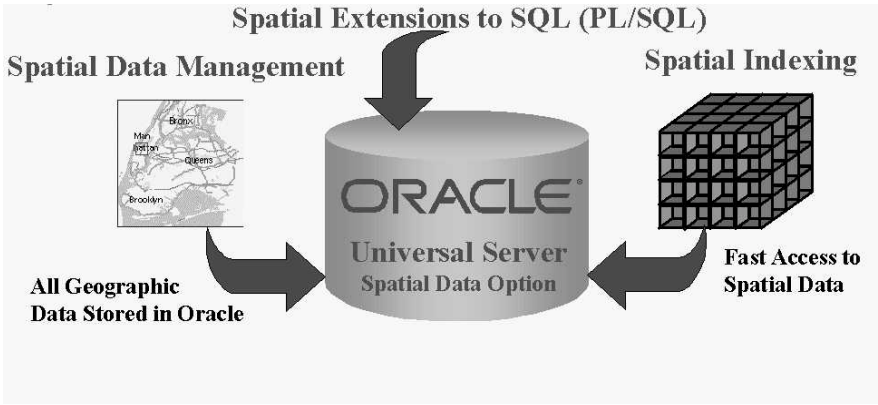

Figure 5.6. Current technology allows integration of spatial and non-spatial data in an enterprise-wide database, or series of linked databases

5.8 Putting the User first

As the modelling process evolves, and becomes increasingly supported and integrated within the new information technologies, the focus on the users must be kept in mind, not least to ensure their needs and requirements are recognised and satisfied.

In order to satisfy the users of subsurface data, a "family" of distinctive delivery products must be provided, each targeted to a distinct class of users. It is necessary to distinguish between the needs and abilities of sophisticated users, including most "researchers", for example, and those of less sophisticated users. While some users can re-analyse or re-process original data, the users amongst the general public usually want an answer, not the original data, not least because they probably cannot process and may not understand it (the "pretty colours and confusion" regime).

The problem focuses on how users can be helped to understand and apply the data, and be aware of its limitations. Geology maps, for instance, are highly interpretative documents. There is a real danger of producing wildly inaccurate products by combining diverse data sets in ways that exceed their scope.

Beyond the technological issues, the question arises as to what are the major operational considerations. Experience suggests that the design of the user interface is critical. The expert wants to enter a request rapidly and precisely; and desires shortcuts. In contrast, the novice needs assistance to understand the options, perhaps with on-line help or tutorials. The novice user would be mystified by the "expert" interface; while the expert will become exasperated with the "novice" interface.

Operational issues involve money. Who is to pay, and how much? The impact of the concept that the "user pays" is familiar, following its application to many services formerly provided by government and now privatised. Use of improved

subsurface characterisation methods would similarly be greatly affected by financial and intellectual property climates.

5.9 Conclusions

Experience to date has shown that good communication is critically important. Generic products are often insufficient and do not meet the needs of any user group particularly well. Fortunately the new information technologies provide mechanisms to place customised products in the hands of different users.

However, the development of such new products requires collaboration. The users must be involved in the creation of the products, and in the design of the user interfaces and delivery channels. While the data acquisition should remain in the domain of the geoscientific experts, the users must be given the opportunity to evaluate HOW and WHY data are acquired and processed.

Fortunately the new technology provides the tools to perform subsurface characterisation FASTER, BETTER, and CHEAPER, just as society's demands for new and refurbished infrastructure increases the requirements for this information.

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6 What are the end-user issues? Settlement risk management in underground construction

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6.1 The North-South Line Metro Project

Until now, metro construction in Amsterdam used cut and cover methods that required the demolition of many historic structures. This resulted in great public opposition to any further expansion of the system. However, increasing population and traffic congestion within central Amsterdam have led to the city council undertaking studies to see if new methods could create a metro without significant surface disruption and to offer complete protection to historic structures. These studies have revealed that it is feasible to construct a metro in the soft-soil conditions which underlie Amsterdam, by using innovative mechanized shield tunnelling methods. However, these studies also emphasized that project success requires careful and extensive subsurface investigations, intensive numerical modelling to predict risk, innovative Tunnel Boring Machine (TBM) design and operations, and real-time monitoring of critical conditions during construction.

After careful consideration of these studies and weighing the alternatives, the city council of Amsterdam decided in November 1996 to permit construction of a new underground metro line, the North-South Metroline. The line is to be constructed in two phases and, when completed, will extend from the north of the greater Amsterdam region to Schiphol International Airport, south of the city.

The first phase of the project will be about 9 kilometres long (Figure 6.1). The section north of the IJ river will run along the surface. An immersed tube construction will be used to pass under the IJ river and the Amsterdam Central Station complex. The line then traverses the historic heart of Amsterdam to reach its southern terminus at the South/World Trade Centre (South/WTC). When this phase is completed, in 2008, it is anticipated that it will be capable of transporting around 160,000 passengers per day.

Constructing the section between Central Station and South/WTC under the historic city centre will be particularly challenging. At least 3.15 kilometres of the total section length of 3.8 kilometres must be constructed using advanced TBM technology in order to avoid surface disturbance and damage to historic buildings. Two individual single-track tubes with an inner diameter of 5.82 m and a bore diameter of *ca.* 7 m must be constructed at depths between 20 m and 31 m.

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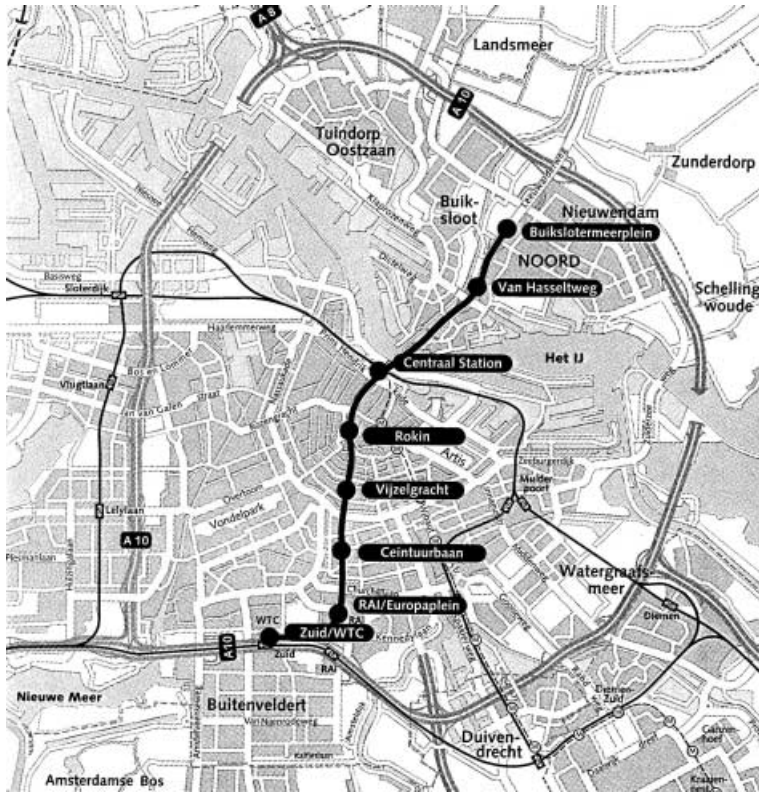

Figure 6.1. The Amsterdam North-South Metroline

Legal stipulations require the tunnels to mostly follow the present street pattern and thus avoid passing under houses or other buildings. However, the narrowness of the existing streets requires the tunnels to be closely spaced, separated by only about 0.5 tunnel diameters, and along one section they must be stacked vertically. In spite of such measures, the minimum curvature allowed for the trains (190 m radius) means that the tunnels will have to pass under a few buildings.

Constructing the section between Central Station and South/WTC under the historic city centre will be particularly challenging. At least 3.15 kilometres of the total section length of 3.8 kilometres must be constructed using advanced TBM technology in order to avoid surface disturbance and damage to historic buildings. Two individual single-track tubes with an inner diameter of 5.82 m and a bore diameter of approximately 7 m must be constructed at depths between 20 m and 31 m. Legal stipulations require the tunnels to mostly follow the present street pattern and thus avoid passing under houses or other buildings. However, the narrowness of the existing streets requires the tunnels to be closely spaced, separated by only about 0.5 tunnel diameters, and along one section they must be stacked vertically.

In spite of such measures, the minimum curvature allowed for the trains (190 m radius) means that the tunnels will have to pass under a few buildings.

This section also includes three deep stations. In order to minimize surface disturbance, these stations will use covered excavations. Diaphragm walls will be placed to depths as much as 40 m, followed by placement of a roof slab. Then the street environment can be returned to its previous condition while the excavations are continued within the walls and under the roof.

This combination of TBM tunnels and station construction methods satisfy the goal of minimizing disruption of normal surface activities. However, prevention of surface deformations and damage to buildings and existing utilities requires careful facilities design and management of construction operations based on detailed knowledge of subsurface conditions. The Amsterdam North-South Metroline project thus provides an excellent example of how the success of modern urban underground construction depends on accurate knowledge of shallow subsurface conditions.

6.2 Geological Characteristics of the Subsurface

The subsurface of Amsterdam is composed of a thick sequence of Holocene and Pleistocene sand, silt, clay and peat layers (Figure 6.2). The oldest Pleistocene deposits are marine clays and fine-grained sands that currently extend far below the surface – some 250 to 350 metres deep. Tongues of Saalian glacial ice eroded a deep basin into these deposits. This basin was subsequently flooded by the sea and partially filled with marine sands and clays (the Eem Clay – Figure 6.2). During the last glacial period, the Amsterdam region was subjected to a periglacial climate and the basin was filled with sand (the Second Sand Layer – Figure 6.2). Younger Holocene deposits consist mainly of peat and clay formed under the influence of an initially rising sea level. About 5000 years ago, a lowering of the sea level allowed rivers to create channels in the existing deposits. These channels, sometimes with widths of over 100 metres contain thin sand and soft clay layers, caused by infilling during to the continued rising sea levels of recent times.

The result of this geological evolution is a fairly consistent stratigraphy of sand, clay and peat layers, as shown in Figure 6.2, with occasional incised river channels. Historical buildings are placed on wooden piles about 15 metres long that are founded in the First Sand Layer. Larger, modern buildings are founded on concrete piles driven to the Second Sand Layer. Tunnel driving will take place almost completely in the Allerød, Second Sand, and Eem Clay units. The tunnels will not directly impact the older shallow pile foundations and, since the locations of the modern deeper piles are well known and not very frequent, avoidance or remedial measures can be taken during construction as required.

The Eem Clay has special significance for the overall advancement of the tunnel. It also will be encountered in the excavations for stations, where it will interact with the braced diaphragm walls. The characteristics of the Eem Clay were relatively unknown before the North/South Line project. Consequently, considerable geotechnical investigations were undertaken.

An important geological consideration is the presence of groundwater beginning about 1 metre below the ground surface. The tunnels and station diaphragm walls are thus subjected to water pressures of around 3.5 bars. Disturbance of the groundwater regime cannot be allowed. Dewatering would likely immediately cause unacceptable ground deformation, but also it would cause deterioration of the older wooden piles. These piles are protected as long as they are totally immersed, partial exposure by dewatering will cause them to decay.

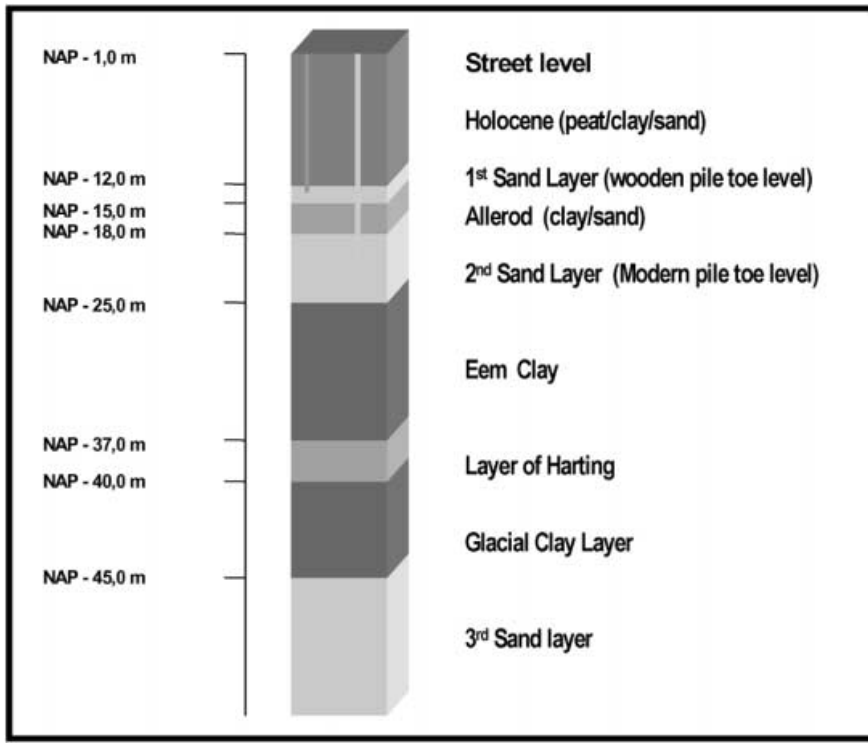

Figure 6.2. Geological stratigraphy typical of Amsterdam.

6.3 Creating a Three Dimensional Ground Model

Dutch engineering practice typically creates a 2D cross-section interpretation by projecting field borings and CPTs (Cone Penetration Tests, Dutch cone or soundings), onto a pre-defined vertical cross-section. When dealing with linear facilities such as roads or tunnels, this cross-section is usually aligned along the trajectory of the project. The observed conditions at each boring location are then classified into standard geological or geotechnical units and these are correlated throughout the cross-section to provide a graphical view of the positions and continuities of

all units. Planning for the North-South Line project required a more complete view of the three dimensional variations of the subsurface, not only along the centreline of the tunnels but also extending some distance to each side.

A 3D Ground Model application, called 3DGM, was developed for the North-South Line project by Witteveen and Bos Consulting Engineers, the project managing consultant. 3DGM was developed as an extension to the Arc/Info GIS package, and can automatically create a three dimensional model of the geological strata forming the Amsterdam subsurface. The approach utilizes a standard definition of the vertical sequence of geological strata (indicated as "Main Layers", or *"Hoofdlagen"* in Dutch) that can be expected in Amsterdam. For instance, in Amsterdam the Base Peat layer is always on top of the First Sand layer. Such sequences are determined from basic geological knowledge, and are applied as boundary conditions by 3DGM. Because, as noted earlier, the basic strata under Amsterdam are sometimes cut by old river channels, it often happens that very local layers are encountered, for instance a clay lens within a thick sand layer. 3DGM allows the user to identify and manually adjust the geometries of such local lenses. The fact that the model is mostly generated automatically makes the input and processing of new information relatively easy.

This 3DGM model defines conditions within a 3D subsurface volume. Geotechnical cross-sections can then be defined along any desired orientation and at any desired position. Such geotechnical cross-sections are generated automatically. Cone resistance values (CPT or SPT, depending on the type of site investigation) and codes defining the geological/geotechnical layers can be plotted on the geotechnical cross-section (Figure 6.3). This makes checking for errors and maintaining an up-to-date geotechnical model relatively easy.

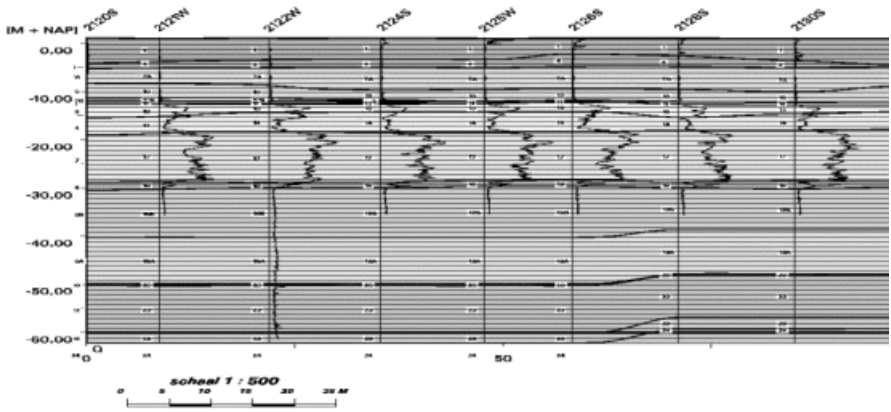

Figure 6.3. Example of a geotechnical cross-section processed within 3DGM, including some CPT logs

Visualisation of subsurface data is one of the most important applications of 3DGM. Cross-sections provide one method of visualisation, as illustrated in Figure 6.3. Contour maps are another 2D display method. 3DGM can create contour maps of the thickness of individual model layers, or of the top or bottom eleva-

tions of particular layers. 3DGM can also produce 3D displays (Figure 6.4). These displays are especially illustrative when the layering is presented in relation to the civil engineering construction. This type of data presentation can lead to an understanding of the ground–construction interaction that was up to now not possible.

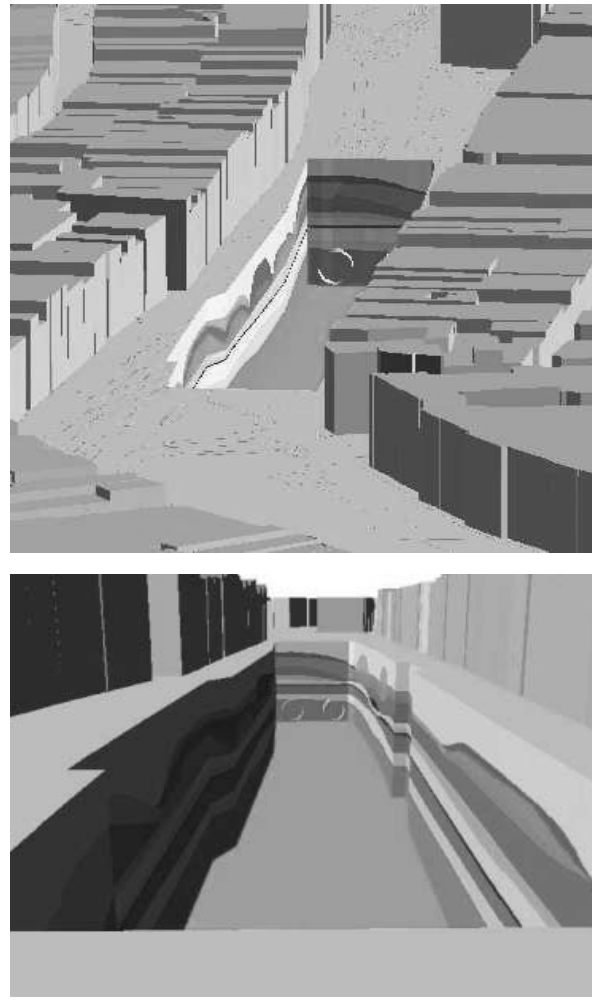

Figure 6.4. 3D visualisations of subsurface conditions encountered in station excavation

The 3DGM model of the subsurface is especially suitable for volume calculations. The volumes to be excavated, subdivided by each geologic unit and construction stage, are readily determined. Figure 6.5 illustrates the calculated volumes of various material types that would be excavated at each construction stage for one of the stations.

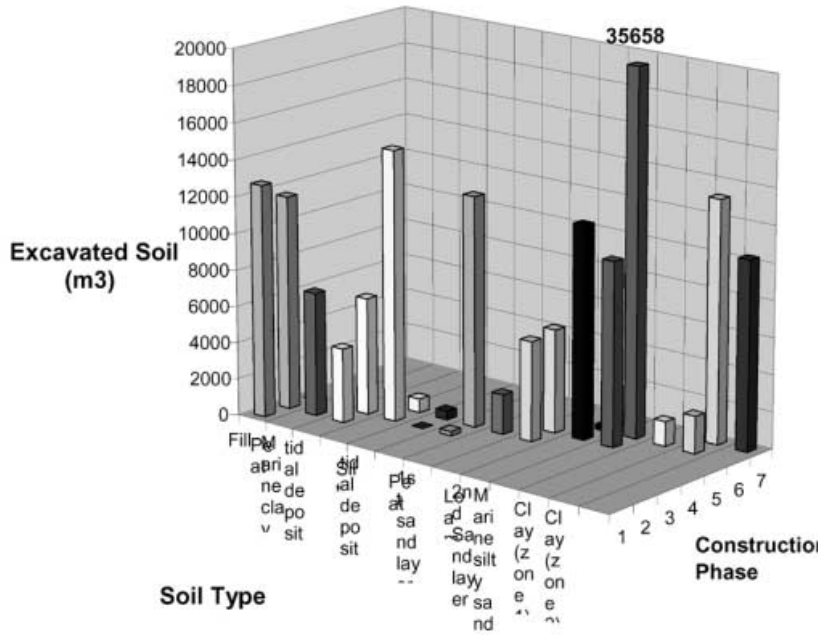

Figure 6.5. Example of volume calculations using 3DGM

Profiles created by 3DGM can be exported to geotechnical calculation software packages for further modelling and prediction. For example, the Mserie analytical software developed by GeoDelft can analyse 2D layer representations along specified profiles to calculate settlement and design directional drilling programs. The Plaxis Finite Element Modelling software accepts a 2D profile to define layers in an element mesh. Generally these numerical applications require much smaller numbers of points than exist within the 3D subsurface model, so the number and density of points can be defined during export from 3DGM, with more points in the zones of interest and less outside these zones.

6.4 Numerical Modelling of Tunnelling Effects

Approximately 1500 historically important masonry buildings, supported by more than 20,000 pile foundations extending to the First Sand layer, are located along the central section of the proposed North-South Metroline. In addition, the proposed tunnel passes below a number of canal bridges and quay walls. A tram line runs along the streets over the entire tunnel boring section and several underground structures are located directly over the tunnel axis.

All these are sensitive to surface deformations, so the North-South Metroline design team had to investigate the risk of settlement-induced damage. Unaccept-

able damage was defined as including not only any kind of functional or structural damage, but also aesthetic and repairable damage. The adopted criteria specified that crack widths could not exceed 2 mm.

A typical masonry structure within the expected influence zone of a TBM tunnel consists of a block of several masonry houses. The house units are connected to one another by common masonry load bearing walls and continuous (front and back) facade walls. The connections between the load bearing walls and the facade walls consist of anchors or teeth constructions between the masonry bricks, which can transmit vertical shear forces between the construction elements. Thus the block behaves structurally as a single construction. An individual house unit is about 7 m wide, about 16 m high and about 18 m long. The load-bearing masonry walls are founded on paired pile-groups placed under wooden cross beams. The pile groups are spaced about 1.2 m apart and the two piles in a group are about 0.5 m apart. These wooden piles are driven into the first sand layer, and are primarily end-bearing – about 80% of the total load (of about 80–100 kN) is transmitted through the pile tip.

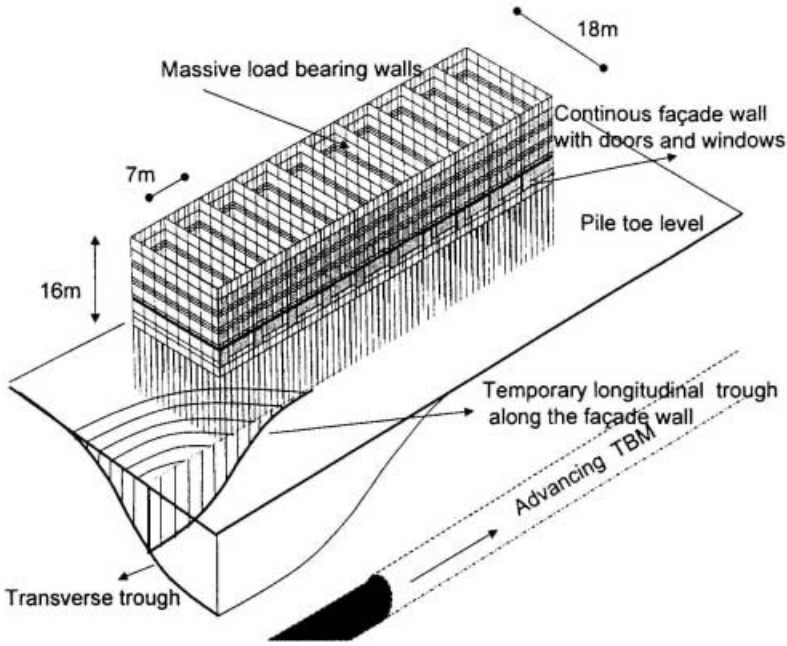

Figure 6.6. 3D model of the block of ten masonary buildings (Netzel, Kaalberg, 2000)

A standardised block of ten masonry houses on pile foundations was used to model building 3D deformations and reactions to ground movements caused by passage of the TBM (Figure 6.6). Netzel and Kaalberg (1999) describe how the GIS capabilities assisted such 3D numerical settlement risk assessment studies.

The results of the study were used to define the boundary conditions and the operating requirements for the tunnelling activities. Program DIANA was used to evaluate the behaviour of masonry walls, the interaction between soil and structure, and the 3D geometric disturbances to the buildings (Netzel and Kaalberg, 2000). The masonry walls were modelled as non-linear plane stress elements, front and rear facade walls included door and window openings. The pile foundations were modelled as non-linear springs to reflect the interaction between soil and pile, including both pile toe resistance and skin friction. The first shield-drive project in Holland, the Heinenoord tunnel, was used as a large-scale testing ground for verification of the theoretical model calculations.

The simulations began with the loads existing prior to the TBM passing the building. Then settlements at the pile toe level imposed by the passing TBM were modelled for a large number of load steps so as to simulate the advance of the 3D-settlement wave along the building. Figure 6.7 shows four stages of 3D deformation behaviour of the standard building block. Passage of the settlement wave causes the building to twist because parts of the building are already undergoing settlements while other parts are still in the initial situation. Even after the passage of the TBM, the imposed settlement trough remains and the building may be deformed toward the tunnel axis.

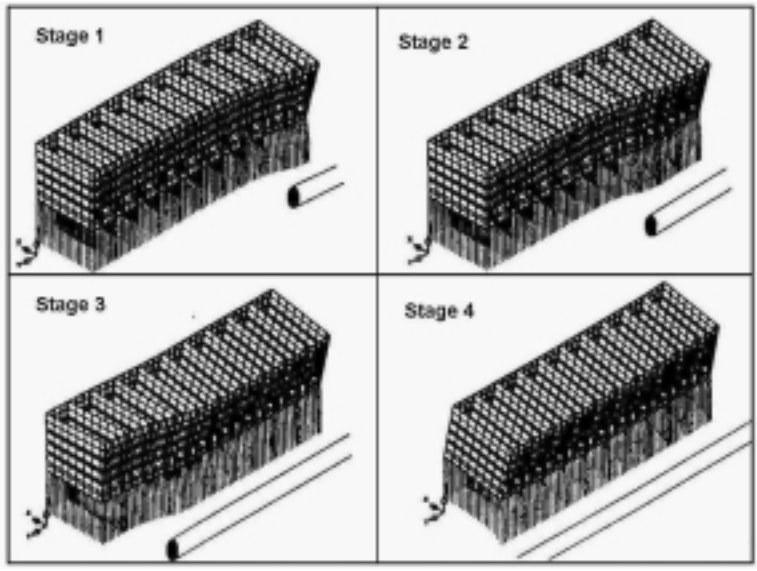

Figure 6.7. 3D deformation stages during and after passage of the tunnel (Netzel and Kaalberg, 2000)

An extensive parametric study was carried out and used to define specific damage criteria for masonry structures of Amsterdam (Figure 6.8). These studies evaluated:

- Material parameters of masonry walls (including E-modulus, tensile strength, brittle and plastic crack behaviour)
- Settlement trough geometries caused by different volume losses and different depths of the tunnels
- Location of the building within the settlement trough – its distance to the tunnel
- Geometry of the end bearing walls. The load bearing walls at the ends of many blocks may have openings for doors and windows. These transverse end walls are referred to further as side facade walls.

Thus far only the passage of a single tunnel has been considered. Since twin tunnels will be constructed, the modelling included settlements caused by passage of the second tunnel. The results of these studies clearly showed that the damaging effects of the TBM are considerably reduced when the depth and distance to the tunnel is increased, or when the volume loss around the TBM excavation is decreased (Netzel and Kaalberg, 2000). This last aspect requires greatly improved TBM performance, and led to the third stage of research for planning the North-South Line.

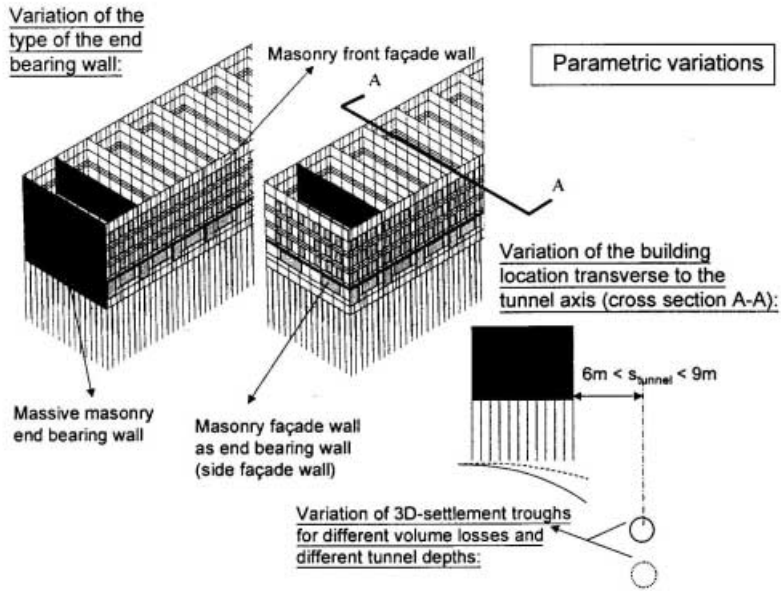
Variation of the type of the end bearing wall:
Masonry front façade wall
A
A
Parametric variations
Variation of the building location transverse to the tunnel axis (cross section A-A):
6m < s_tunnel < 9m
Massive masonry end bearing wall
Masonry façade wall as end bearing wall (side façade wall)
Variation of 3D-settlement troughs for different volume losses and different tunnel depths:

Figure 6.8. Parametric variations (Netzel and Kaalberg, 2000)

6.5 The Integrated Boring Control System (IBCS)

Initial feasibility studies for the North-South Metroline revealed that existing state-of-the-art TBM methods in soft soils produced a 1–3% volume loss around the tunnel. This would produce excessive surface deformations and building damage. Because extensive mitigation along almost the entire length of the route would be too expensive, the only alternative was to focus on improving the quality of the TBM process. Analysis of potential innovations to TBM techniques identified a compact version of the variable (vario) shield system that could be adapted to meet the project requirements (Figure 6.9). This shield could assist in reducing the degree of volume losses and subsequent surface deformations (Kaalberg and Hentschel, 1998; 1999). However, the analyses also showed that the use of such a high-performance shield system would provide only a partial solution. The minimal surface deformations demanded by Amsterdam could only be achieved by precise operation of the TBM system, and this depended upon effective process control. This understanding logically led to the consideration of a process control system concept that has been named the Integrated Boring Control System (IBCS).

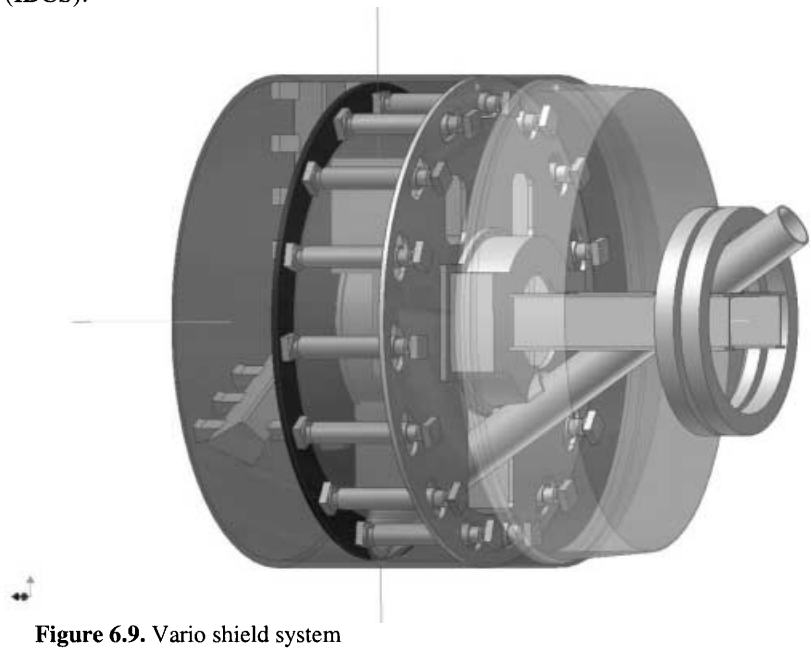

Figure 6.9. Vario shield system

The IBCS design uses information concerning ground conditions as well as monitoring the operation of and the effects caused by the TBM. In this way interactions with the soil and the pile foundations can be constantly evaluated and potential damage to buildings controlled. Diverse open- and closed-loop control systems are already used by current tunnel boring systems. However, the IBCS concept is distinctive in that it integrates settlement information into the control parameters.

This allows the tunnel boring process to be controlled not solely on the basis of tunnel and machine data. Rather, IBCS control and operational criteria reflect settlement information provided in real-time as the TBM advances.

Figure 6.10 illustrates the basic IBCS process and its relational links to data acquisition and the tunnelling system operations. The initial version of IBCS contains three major components – an Effect Measurement component, a GIS Database component, and a Prediction component. These are shown in the lower right portion of Figure 6.10.

The Effect Measurement component accepts and integrates real-time data from the TBM (TBM and boring process parameters) and from the surroundings (monitoring systems in the ground and on piles and buildings). These data sources are shown across the top of Figure 6.10. The crucial point is that real effects are provided to the IBCS. Modern measuring processes, linked to the IBCS on-line, provide continuous and simultaneous data acquisition for all monitoring sites. Relevant boring process variables are extracted from TBM measurements. Together, these data streams allow the IBCS to evaluate the real process as the tunnelling progresses.

The GIS Component performs three distinct functions. First, it contains and maintains the 3D subsurface geological and geotechnical models described in the previous section. Second, the GIS component accepts information obtained and processed by the Effect Measurement component and uses this new information to up-date and improve the pre-existing 3D model (Netzel and Kaalberg, 1999). Third, the GIS provides accurate visualizations required for rapid analysis and interpretation in the Prediction component.

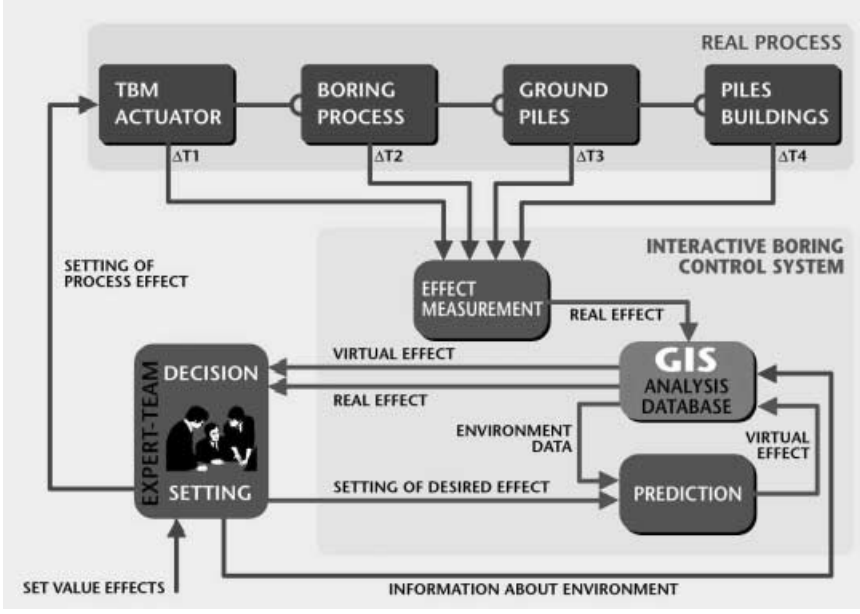

Figure 6.10. Process structure with the Integrated Boring Control System (IBCS)

The Prediction component performs predictive calculations and comparisons. Prior to the actual tunnel construction, a virtual boring process is modelled using a 3D FEM numerical model that incorporates determinative process parameters for the TBM and knowledge of the subsurface conditions surrounding the advancing tunnel. This numerical model evaluates the reactive forces in the bore front and annular void areas and assesses how these will be transmitted into the surroundings. This permits predictions to be made concerning soil deformation and settlement. The Prediction component also uses the 3D subsurface model maintained within the GIS component to combine predictions based on numerical models with current observations. Simultaneously the boring process settings are being monitored and displayed. The result is a closed, real-time information circuit for the IBCS.

In the initial development stage of IBCS, the Decision-Setting functional unit is a purely information and visualization system that monitors the TBM processes and extracts relevant process variables. Adjusting the process parameters while observing the actual effect data permits the process sequence to be successively optimised so as to minimize settlements. Decision-making and adjustment must continue to be carried out by humans, acting as an expert team. This is illustrated on the lower left portion of Figure 6.10. Real-time visual displays of the boring process variables, along with data defining the predicted and actual settlements, will be produced at the TBM control panel. These displays provide the basis for decision-making by the process control team. It is anticipated that subsequent versions of IBCS will incorporate calculation algorithms to produce a more nearly fully automated process control system.

However, even with this semi-automated operating mode, the IBCS demonstrates the importance of creating and using 3D subsurface models. The displays utilize previously conducted numerical models, as well as current observations. Interpretations of both models and observations depend on the 3D subsurface model. When combined with experience in TBM operations, and knowledge of the importance of various process variables and operating parameters, this initial IBCS can result in greatly reduced settlements caused by TBM operations. It allows TBM operators to make better and more rapid operational decisions, based on an extended experience base, while also reflecting both site-specific and real-time conditions.

6.6 End-User issues

The development of TBMs has evolved from how these machines can operate efficiently in diverse ground types (from rock to soft soils) to how TBM operations can be optimised to provide minimal ground deformation, especially in soft soils. In a vulnerable urban environment, such as along the central section of the Amsterdam North-South Metroline, the question becomes what TBM performance is required and what level of performance can be achieved. Then questions arise concerning the quality and quantity of the subsurface geo-information required to achieve this high performance level.

The North-South Metroline project undertook an extensive site investigation programme in order to establish the relevant geotechnical units and their parameters. The project determined that a high-quality 3D subsurface model was required to represent the layers of geological and geotechnical units beneath Amsterdam. The 3DGM software was developed to fulfil this need. Previous tunnel projects used only one large-scale longitudinal geotechnical profile to characterize the subsurface conditions. The North-South Metroline project used 3DGM to create a true 3D representation of the subsurface along and adjacent to the entire project. Because 3DGM was linked to a GIS a powerful and easy-to-use 3D model was available to provide high quality information during all project phases. Processing and updating of the model involves automated processes. Instead of using the traditional single centre-line section, 3DGM allowed the project engineers to generate custom cross-sections at any location and orientation desired.

This flexibility gave the engineers an opportunity to make more sophisticated analyses. For example, cross-sections were developed with 10 m spacing along the entire project length. These were used to provide subsurface conditions to numerical models predicting settlements, and building deformations. However, one should always be aware of the 3D subsurface model reflects the quality of the input data. In urban areas, the choice of locations for ground investigation is generally limited by the existing land usage, so the 3D model produced by 3DGM, or any other method, may have limited accuracy in at least some locations.

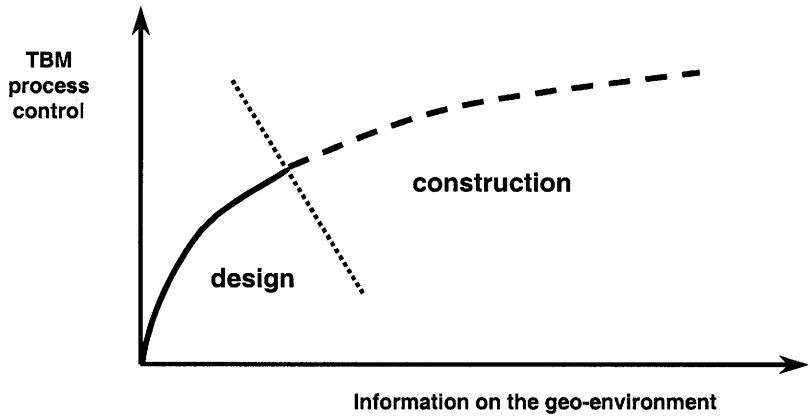

Figure 6.11. Relationship between degree of TBM control and amount and quality of geological information (Haasnoot and Maurenbrecher, 1997)

Figure 6.11 schematically gives the relationship between the degree of TBM process control and the amount and quality of information on the geological environment (Haasnoot and Maurenbrecher, 1997). In the design stage, only a limited amount of geological information, for instance basic soil or rock conditions, results in a rapid increase in the degree TBM process control, and the curve rises rapidly. The addition of more geological information, often involving much more detail and consequently much more effort and expense to obtain, in the later con-

struction stage may only provide more modest improvements in the degree of TBM process control. Thus, the challenge for the geological professionals is to determine whether ground investigation can be enhanced so that a significant increase in TBM process control can be achieved.

From the users point of view, such considerations suggest that the best strategy for the acquisition of geological information should be guided by an approach that can be called **Value Ground Investigation**. This approach suggests that additional efforts should be expended to acquire information only if that information can be expected to immediately enhance the control of the construction process. This approach can be established by integrating an appropriate site investigation tool or indicator into the construction process. If used correctly, the approach will provide high quality information at the exact location of interest. To use this newly acquired information in the construction process, models or algorithms will have to be developed that are capable of processing this information in real time and advising the construction process of appropriate modifications or adjustments. Based on experience with the Amsterdam North-South Metroline, it appears that this **Value Ground Investigation** should form the paradigm for the geoscientists for the coming decade.

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7 Data requirements for geo-environmental management: end-user and producer perspectives for a harbour

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7.1 Introduction

Of particular relevance to harbour management are the societal demands for environmental care, both within the harbour itself and in its vicinity (ABP Research, 1999). However, the economics of harbour operation do not encourage individual contractors or government agencies to fully consider the long-range effects. An additional problem for environmental monitoring of harbours is the lack of consistent documentation of basic sediment-related features. Integrating the interests of science, industry and social sectors is clearly desirable from a holistic viewpoint, but is limited by lack of compatibility of data and documentation. The quantity of data now being produced by modern digital instruments increases the extent of this problem. There is now a need to define an appropriate database structure (Burton et al., 1999) and to establish recording routines which can permit flexible use within future, yet-to-be-defined contexts.

7.2 End-user and provider perspectives

Sustainable management regarding silting and pollution in harbours is essentially focussed upon the following questions:

1. "Where, when, and how much?"
2. "With what effect?"
3. "How to evaluate the alternative preventive or remedial actions?"

Such questions can be addressed by extensive monitoring, essentially attempting to measure the parameters influencing each question for each site and occasion. The other extreme is to try to theoretically predict the effects of the physical and geochemical processes involved. Either approach is limited by lack of feasibility as well as economic restrictions.

A hypothesis is now presented that an optimum balance can be achieved between experimental control and site relevance, combined with the predictive value

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of process studies together with the necessary confirmatory documentation achievable by monitoring, i.e. site-specific measurements (Figure 7.1).

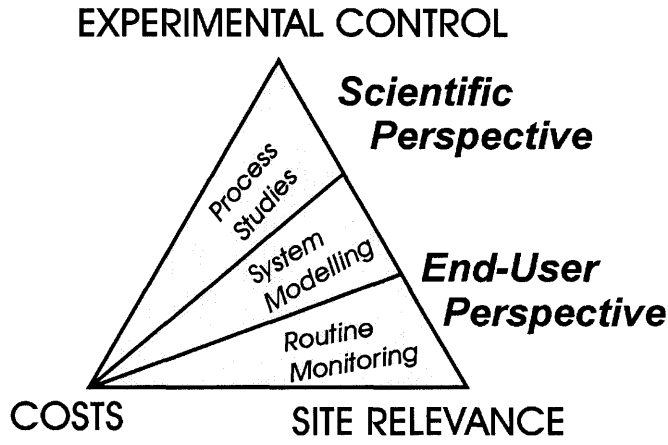

Figure 7.1. The combination of processes studies, modelling, and routine monitoring must be balanced by cost considerations, where none of these individual activities are economically optimal nor environmentally responsible (after Newson, 1992)

In addition to offering cost effectiveness, the application of modelling to combining the processes of evaluation and monitoring will help safeguard the environment since a single investigation cannot alone measure the response of the system to future changes or indicate when threshold conditions might be exceeded. Furthermore, a site-specific, engineered approach to harbour management would tend to address the individual problems associated with each project. The danger of such an approach is apparent when processes are interrelated and the system response less predictable than suggested by simply expressed relationships.

"Experimental control" refers broadly to scientific evaluation. In the case of a large-scale natural system this may involve comparing the influences and effects of processes recorded in similar environments or changes recorded over time within one setting. In this respect, sediment investigations have a major advantage over many other types of environmental monitoring in that sediment accumulation represents a time-integrated, net effect of environmental processes.

Sediment sources, transport pathways and accumulation rates can be estimated using water-current measurements, data from sediment traps or tracer studies. However, such methods are time-limited and generally become less accurate as the intensity of the processes involved increases, such as during storms or intensive ship traffic, perhaps the most decisive time for their total influence upon the environment.

A natural filtering of the temporary changes and a record of the summed effects over yearly or longer cycles should complement the short-term measurements. The value of sedimentological studies would contribute to the strong relationship that normally exists between particle size, organic-matter content and geochemical reactivity, including the level of heavy metals and organic contaminants (Håkans-

son and Jansson, 1983; Salomons et al., 1988). Since natural processes operate at different scales and magnitudes, in both time and space, and interact with man's utilisation of his environment, it is imperative to recognise those factors that can be manipulated and those that cannot. For instance, the prediction of siltation and the evaluation of pollution risks are essential tasks contributing to harbour sustainability if the sediment sources, transport pathways and the sites of accumulation can be identified and to some extent quantified.

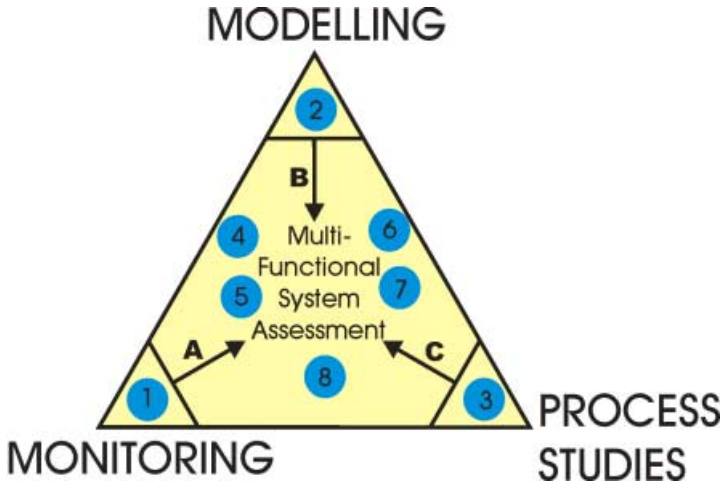

Figure 7.2. The priorities within a single harbour investigation are often related to relatively short-term goals, as illustrated by the 8 examples (circles, explained in the table below). The arrows (A–C) indicate motivating considerations for a more balanced use of activities investigative.

End-User Objectives (illustrating typical input combinations)	
1	Harbour sediment testing prior to dredging.
2	Modelling with archive data or with theoretical principles when no data are available.
3	Sedimentological studies of a siltation or geochemistry at a specific site.
4	Harbour study regarding expansion or other construction changes.
5	Environmental Impact Assessment regarding siltation or pollution conditions.
6	Geological or hydrological evaluation of a sedimentary environment.
7	Theoretical extension of sedimentation conditions interpreted from selected sites.
8	"Ground-truth" testing of a process interpretation.
Motivating Criteria for Multi-Functional Assessment	
A	Need for greater predictive capacity, both spatially and over time.
B	Need for greater data control and basis in theory.
C	Need for greater applicability with changed conditions.

The approach to evaluating the routine monitoring can also be considered to represent the perspectives of an end-user, whereas process studies correspond essentially to the scientific producer perspective. The premise pursued here is to combine these perspectives, leading to a more complete basis for evaluation and improved cost effectiveness for harbour geo-environmental management. Such conflicts of interest are typified by the history of dredging in the New York harbour (Steward, 2000).

The methods of sedimentological study need to be adapted to the harbour setting. These methods should be standardised as much as possible for each stage of the study, from planning the sampling procedures through laboratory testing to interpretation and dissemination. The choice of routine procedures needs to be based on detailed surveys at selected sites, aiming to estimate variability in the sediment parameters. This should lead to a simplified sampling scheme; indeed, the use of proxies for sediment characteristics may be justified in subsequent investigations. The flexibility to incorporate new aspects is nevertheless necessary within any documentation procedure adopted.

7.3 Harbour site investigations

The inclusion of scientific goals within a monitoring programme is possible with prudent choices regarding sampling and documentation routines and by selective complementary analyses. The additional costs of each new task are necessarily an issue, and the overall environmental and economic advantages are the motivating arguments that need to be more clearly specified for harbour management. Only a few of the suggested methods listed in Table 1 are now taken up, dealing with sediment documentation for immediate and archive purposes, priority sediment parameters, and evaluation techniques. Others methods are not necessarily unfavourable, but any site investigation programme will have a similar cost-benefit evaluation for method selection.

7.3.1 Documentation Methods

The balance between achieving short-term goals and the future utility of sedimentology data is governed by the choice of sampling and documentation protocol. The spatial coverage will necessarily limit the overall applicability of the database. Rapid (inexpensive) methods are preferred, particularly if information can be recorded without the need for interpretative input.

Digital photography of box-cores meets these criteria (Figure 7.3). Box-coring is suitable for fine-grained sediments in relatively shallow water, where surface disturbance can be detected and visually controlled and, if necessary, complemented by parallel, piston cores. If intact, the sediment surface area (ca. 0.2 m^2) observed in box-cores is significantly greater than obtained by other coring techniques.

Functional facies (representing environmental conditions on the sea floor) can be classified using sedimentological and biological features, but such a classification can be applied later if the upper surface and the vertically sectioned box-core sediments are photographed. The relatively large quantity of sediment also facilitates sub-sampling for laboratory analyses and geotechnical testing from specific intervals. The turn-around time for sectioning, photographing and sub-sampling and clean-up is approximately 10–30 minutes once the box-core is recovered, often comparable to the time required for travel to and positioning at the next site.

Table 1. *Selected techniques that warrant greater utilisation in harbour sediment investigations. The motivating considerations and limitations are considered from different perspectives.*

Documentation Methods	End-user Perspective	Scientific Perspective	Multi-Functional Perspective
Box-coring and digital imagery	Inexpensive. Allows extensive sampling of specific levels. Easily incorporated into routines.	Sampling can disturb sediments. Records valuable information for future, unknown purposes.	Documentation of multi-disciplinary features feasible for non-specialists. See also Bottom Surface Class.
Smear slides and sediment archives	Requires very little space and training. Time-related changes are recorded as baseline information.	Sediment composition and grain size can later be estimated and evaluated by specialists.	Future techniques may likely increase the value of small sample archives. Complementary to lab analyses.
Priority Sediment Parameters			
Particle size	Generally recognised as important, but still avoided to save costs or assumed to be homogeneous within an environment. Some analyses should always be included.	An essential parameter for sedimentological evaluations and normalisation for sample comparisons. Automated analyses and entire distribution records are preferred.	To reduce costs, smear-slide estimations and proxies (e.g. Al, Sc, Li, quartz/feldspar ratios) may be used once relationships are established. Digital archives possible.
Organic matter content	Similar arguments as grain size, above. Loss on Ignition is only approximate, but may be sufficient following site-specific calibration.	Major influence upon redox conditions. Strong correlation with contaminants, but also with particle-size variations.	OM is an essential link between biological, sedimentological and geochemical evaluations. See also geochemistry, below.
Component-specific geochemistry	Relatively expensive and requires expertise for evaluation. Metal speciation usually not included in routine surveys.	Metal speciation and organic specification is necessary for evaluating the bio-geochemical process affecting contaminants.	The specification of chemical components is important for understanding contaminant mobility and other sedimentary conditions.
Evaluation Techniques			
Grain-size interpretations of sediment transport	Requires expertise, but provides information of an important net effect.	Good connection between process interpretations and monitoring databases.	Provides a basic description of net transport conditions. Diverse practical applications.
Multi-parameter normalisation	Parameter relationships may allow use of proxies for effective routine procedures.	Site-specific associations accounted for by primary sedimentological data.	Combines physical and geochemical and, in some cases, biological observations.
Functional Facies Classification (sediment types)	Comprehensive archive function without strict technical requirements.	Allows scientific evaluation much later than site survey documentation.	Stresses the integration of physical, geochemical and biological factors.

The sediment surface reflects the recent environmental conditions, especially regarding transport and depositional processes, but also nutrient supply and other influences upon the bottom fauna. For example, the presence of a filter-feeding fauna implies a certain supply of detrital organic particles, but with limited reworking at least moderate sediment firmness, and aerobic conditions. With further study in a particular environment, the Functional Facies classes (see also below) could be associated with more specific features regarding water salinity, current activity, pollution levels (cf. Salazar-Jiménez et al., 1982; Boyd and Honig, 1992) or redox conditions of the sediment (e.g. oxic, mixed, or anoxic; Myrow and

Landing, 1992; Rosenberg et al., 2000). In turn, surface colonisation has a well recognised importance for current baffling, enhanced sedimentation, and stabilisation (e.g. Almasi et al., 1987).

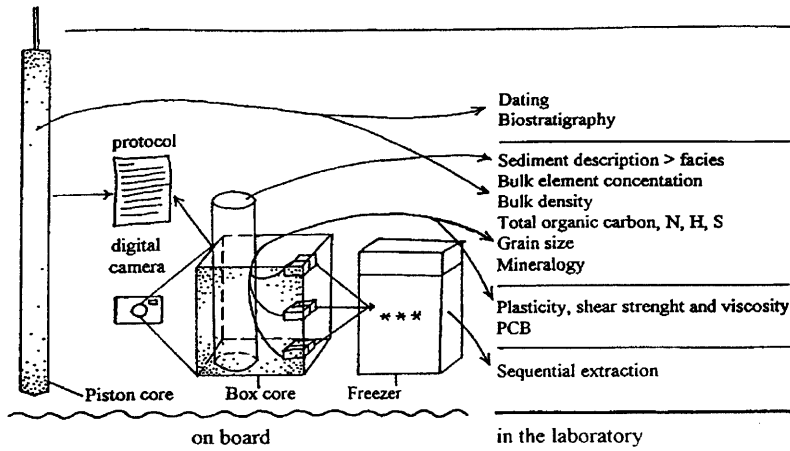

Figure 7.3. An illustration of complementary sampling, sedimentological documentation and sub-sampling for various subsequent analyses (Stevens et al., 1999)

A second type of sub-sampling is suggested for microscopic work and for long-term archives. Smear slides are traditionally used for deep-sea research (e.g. Rothwell, 1989). A very small amount of fine-grained sediment is "smeared" and affixed to a glass microscope slide with epoxy or similar mounting medium. The slides are appropriate for estimating particle size distribution, particle texture and composition (mineralogy, organic matter character, biological constituents) and, importantly, the aggregate and other structural associations existing within the different components. Smear slides can be easily stored for later utilisation if finance, expertise or instrumentation is not immediately available.

Environmental change can only be appreciated through temporal comparisons. In this respect, future questions may arise that are not immediately important or apparent. Future theoretical or technical developments may permit new investigations using the small amount of material stored in a smear slide or sediment archive (Stevens et al., 1999). It is recognised that even the most ambitious documentation may still prove unsatisfactory. Sediment archives should therefore be given a high priority within the project management programme.

7.3.2 Sediment parameter priorities

Although there are numerous parameters that are valuable for sediment characterisation, most of these are quickly excluded from site investigations because of cost or time limitations. On the other hand, restricted measurements of chemical or geotechnical properties concerned with pollution or construction projects may ad-

versely increase the risk of erroneous sediment treatment. In addition to the visual documentation of box-core sediments suggested earlier, a few detailed analyses of selected sites would strongly enhance the documentary value of any investigation. The sediment parameters having greatest influence on measuring the degree of pollution are (Table 1): particle size, organic content, and component-specific geochemistry.

Particle size is essential for assessing sedimentological processes involved with transport, accumulation and post-depositional change. Since much of the organic matter is transported together with the finest, mineral particles, the clay content derived from a particle size analysis is often closely correlated with organic content. Both clay and organic matter are important because their large surface areas provide effective carriers for adsorbed pollutants, and their distribution in the environment is related to the prediction of contamination (Buckley and Cranston, 1991).

The interpretation of transport pathways is facilitated by considering the successive changes in particle size between adjacent sites (McLaren, 1981; Gao and Collins, 1991; Stevens et al., 1996). This methodology is particularly useful in environmental studies because it reflects the time-integrated, net effects of many complicated processes that are difficult to measure and model representatively.

Total-sediment geochemical analyses do not necessarily give an accurate measure of pollution risk since the bonding character of each contaminant influences mobility and reactivity. The natural background occurrences of metals can vary, masking the contributions from anthropogenic sources. Thus a certain level of geochemical documentation of specific components is desirable to evaluate their individual contribution to the total-sediment geochemical composition. The geochemical "speciation" of different components is done by sequential leaching of the sediment using increasingly strong fluids (Tessier et al., 1979; 1982). The operationally defined components are the exchangeable phase, carbonate phase, oxides, sulphides, organic matter, and residual phases. Size-specific fractions (e.g. clay or <63 μm fractions) may be separated and characterised to evaluate the influence of particle size (e.g. Loring, 1991).

Normalisation is generally done in order to reduce the interdependency between parameters. Although normalisation with clay or organic matter is most common, the combined use of component-specific geochemistry and the clay and organic-matter allows normalisation to be carried out, proportionally weighted according to the contribution from each phase or fraction (Krijgsman, 1996; Van den Hurk et al., 1997; Engström and Stevens, 1999). Comparing the degree of pollution between sites or vertically within a profile (reflecting environmental change over time) becomes more justifiable following pollutant normalisation, helping identify sources and dispersion pathways, but it is always prudent to consider maps of the original data in order to ensure a logical interpretation consistent with the facts.

7.3.3 Multi-functional considerations

Management of information from a complex environment such as the sea floor is a formidable task, especially when documented on separate occasions by different

investigators, probably with differing objectives. The use of a sediment facies analysis, traditional within geology, provides a valuable framework. The application and extension of this concept to modern environments emphasises the 3D character of sedimentary deposits and the inter-parameter relationships (Figure 7.4). Each "Functional Facies" class integrates the physical, geochemical and biological parameters of the bottom sediment, and can be further linked to regional geographic settings. Interpretative implications are kept separate from the descriptive function of the facies, but the facies division should ideally be chosen considering the intended detail of the subsequent assessment. The functional facies documentation should be structured in such a way that permits new input of data, changes in classification, or re-evaluation of relationships.

The Functional Facies classification is seen as providing a useful summary of data from various sources. Many monitoring programmes include water, biological and sediment parameter documentation, which are individually important but not independent. Since additional sampling and parameter analyses will likely be limited by cost, proxies and relationships established within each of the Functional Facies classes can be utilised to economise, so that single parameter trends can be used to extrapolate the other features related to a particular functional facies. This is considered to be particularly important for pollutant classifications, where normalisation routines and toxicity tests are too expensive to be carried out at each site.

Selection of sub-populations within these parameters relative to each Functional Facies increases their site-specific value. Significant differences in the parameter relationships should be used to refine threshold values for establishing the presence of contamination. They can also be used to improve sampling strategies that do not violate the sub-population boundaries related to the spatial impact of the environmental processes. In particular, bioassay and benthos community evaluations are being increasingly favoured for direct testing of toxicity, but their extension beyond control sites requires a rational basis related to the sea floor variability.

Functional facies can help improve interpretations and help maximise the applicability of (expensive) analyses. Furthermore, the need for future monitoring and complementary laboratory analyses will be more apparent within such a framework. The use initial Functional Facies classification from box-core descriptions and the subsequent environmental evaluation has been demonstrated in the Göteborg Harbour (Stevens *et al.*, 1999; Stevens, *in press*).

Additional problems within multi-source and multi-functional data sets arise from the differences in scale and objectives of the original investigations. The top-down and bottom-up perspectives focus upon alternative factors that can best be related to each other within the holistic system, whereas most investigations are usually carried out on a more restricted basis. Integrating quantitative and qualitative knowledge is often unavoidable. However, the evaluation can be facilitated using a systems methodology such as interaction matrices for a given scenario, followed by system dynamics analysis (Hudson, 1992; Scholz and Tietje, 2002) and fuzzy-set logic for predictive modelling (Burton *et al.*, 2002).

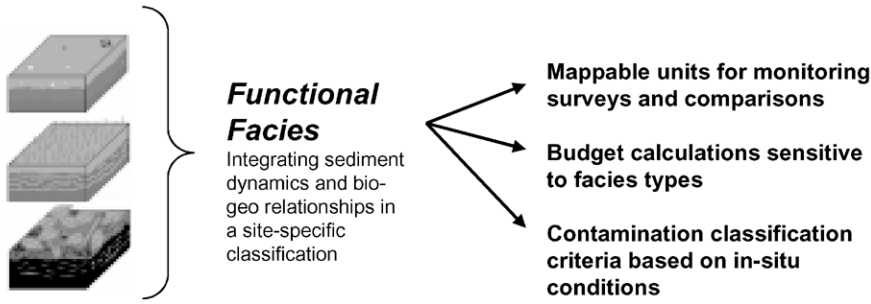
Functional Facies
Integrating sediment dynamics and bio-geo relationships in a site-specific classification
Mappable units for monitoring surveys and comparisons
Budget calculations sensitive to facies types
Contamination classification criteria based on in-situ conditions

Figure 7.4. Functional Facies are using 3D sediment characteristics, providing distinctive units that can be mapped, related to sea-floor processes, and used to give parameter relationships an increasingly specific character (after Stevens *et al.*, 1999)

7.4 Conclusions

With foresight, the results of routine monitoring and studies directed towards specific project goals can contribute to a database with multi-functional capacity. The selection of appropriate documentation methods, establishing the priority parameters for detailed analysis and setting up archive procedures, is important.

Recommendations regarding site surveys have been illustrated utilising box-cores. Fine-grained sediments only need small, easily stored sub-samples in order to facilitate considerable future utility. Determination of particle size, organic content, and component-specific geochemistry are believed to be the most useful components. These parameters offer cost-effective value for evaluating the sediment conditions, the degree of pollution, and the potential changes in the environment with time.

A bottom-sediment classification based on "Functional Facies" is recommended in order to integrate visual observations of core samples with laboratory analysis results. The importance of physical, geochemical and biological interactions within the sediment environment is also stressed, in connection with the need for normalisation and classification of polluted sediments.

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8 A decision support system for groundwater: water management issues for opencast mining

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8.1 Introduction

In many East European countries brown coal mined in open pits has been for many years the major source of energy for industrial and domestic usage. For instance, in Poland ca. 70 M tonnes of brown coal are mined per annum, 6.9% of total world output. In the Czech Republic opencast mining yields ca. 58 M tonnes of brown coal per annum. The mining equipment requires dry conditions, thus open pits need intensive dewatering. As a result of groundwater abstraction, huge depression cones are formed affecting ground water over an extensive area, perhaps 5–10 times larger than the pit itself.

Groundwater disturbance causes several environmental problems: potential drying up of water supply wells and surface sources; effective disposal of abstracted water; avoiding the precipitation of mineral salts from the groundwater and significant changes in water quality from changes in the pumping regime.

Resolution of such problems requires compromise between the mine operators and the regulatory authorities. The desired outcome should be environmentally sustainable. Furthermore, appropriate decision making for both parties has to depend upon reliable data as the basis for predicting the behaviour of the groundwater regime. Such predictions are limited by the (considerable) uncertainty associated with data of poor quality. When combined with uncontrolled redistribution of abstracted groundwater, this turns the sustainable management of groundwater resources in the vicinity of opencast mines into a formidable decision problem.

What is needed for is a consistent framework for resolving groundwater-related problems and conflicts caused by mining. The basic philosophy of a decision support system is discussed, developed by the Warsaw University of Technology (Poland), Aquatest (Czech Republic), Sogreah (France) and Trinity College Dublin (Ireland) within the INCO Copernicus Programme for the mining area of Konin (Western Poland).

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8.2 Impact on groundwater

Mine dewatering disturbs the regional groundwater balance, but is only one of a number of influences affecting the groundwater regime. Others include: agriculture, industry, public water supply and private wells. Dewatering of opencast mines may adversely affect surface water on a regional scale by:

- reducing water availability for forestry
- draining rivers, lakes and wetlands.

In addition to such water-related effects, a 'marching' open pit may cause undesirable modifications to the general environment over a characteristic time scale:

- devastating the pre-existing landscape (transitional – 10–50 years)
- modifying the soil (transitional – 10–50 years)
- modifying the deeper subsoil (practically permanent)
- generating noise (transitional – 3–5 years).

Except for noise (which is commonly considered to be transitional) and modifications of the deeper subsoil (which people do not care much about) the duration of the first two mine-generated environmental effects is comparable to the human life span. Other transitional phenomena such as lowering the water table and the level of lakes and rivers have somewhat longer 'time scales' of 70–100 years, affecting more than one generation of people living in the vicinity.

In general, groundwater-related conflicts with open pit mines are triggered by:

- competition for the region's water resources
- disturbing *vs.* protecting the environment of the region.

Issues of the second type stem from the inevitable 'marching and dewatering' in time and space by the opencast process, modifying subsoil and water resources of the whole region. The opencast mines act contrary to the statutory responsibilities of the local authorities, tasked with environmental protection. Conflicts that arise are inevitably difficult to resolve as the two principal authorities (mining company and local authority) represent wider interests. Opencast mines are mostly driven by national interests of energy supply whereas local authorities represent the regional interests of the population and ecosystem.

Resolution of conflicts between mines and the other users of groundwater resources is complicated by the representation at different levels of social interest. For instance, individual owners of wells abstract groundwater for domestic existence; agriculture and industry are driven by economic forces or regional development policy.

In general terms, sustainable development in an active mining area faces making decisions within a complex system; conflicts are convoluted and knowledge about the system's objects and processes are uncertain. Uncertainty and impreci-

sion concerning the groundwater system creates a formidable challenge when trying to resolve such conflicts.

8.3 Making decisions

Groundwater-related conflicts mainly concern the physical state, but it is their social context that makes them so complex. It seems that consensus is the only way to settle matters. What generally helps in attaining consensus is transparency and knowledge that can be achieved through measures such as:

- improved measurements and data collection of the ground profile
- improved processing and presentation of the ground profile (requirement for databases, modelling, 3D visualisation)
- decision making methods that explicitly take uncertain knowledge and imprecision of the data into account.

Trends in the domain of information technology indicate that the tools and methods required to describe and control the ground are getting sharper, cheaper and more reliable. Availability of such tools by all parties will facilitate reaching a consensus in conflicting situations, provided the rules are simple:

- ensuring the tools for data acquisition are accessible to all parties concerned with the mining area
- presenting the data in a consistent manner
- educating those concerned with the conflict as to how the methods of data interpretation work and what their limitations are
- bringing those in conflict together and facilitating dialogue.

8.4 A case study from the Konin region of Poland

Opencast mining of brown coal has governed the social life and economy of the Konin region in western Poland from the early 1950s until the present day.

Individual users of water have accused the mining companies of taking water away from them, resulting in dispute resolution in court. Many of the suits were falsely based, lacking basic knowledge of the ground profile and related groundwater processes. Since the 1980s, environmental and water issues have been seriously considered by local authorities, such as with the attractive lakes located north-west of the mines in danger from dewatering operations (Figure 8.1).

From the outset of this conflict, the Institute of Environmental Engineering Systems at the Warsaw University of Technology has been studying the dispute between the Konin open pit mines and the local authorities. The conflict resolution needs a consensus concerning the extent to which the regional groundwater can be

modified, yet also be protected. The complexity of the situation became clear from the outset. In particular, the uncertain structure of the ground profile and the dynamics of the groundwater processes were subject to controversy. However, by the late 1990s, geological, hydrological, environmental and economic evidence had reached a 'critical mass', but there was too much to process and analyse. Thus was born the idea of disregarding most of the biased and contradictory expertise and together creating just one shared ground database, thereby allowing the mining companies and the other interested parties to reach agreement concerning the factual data and methodology (Figure 8.2).

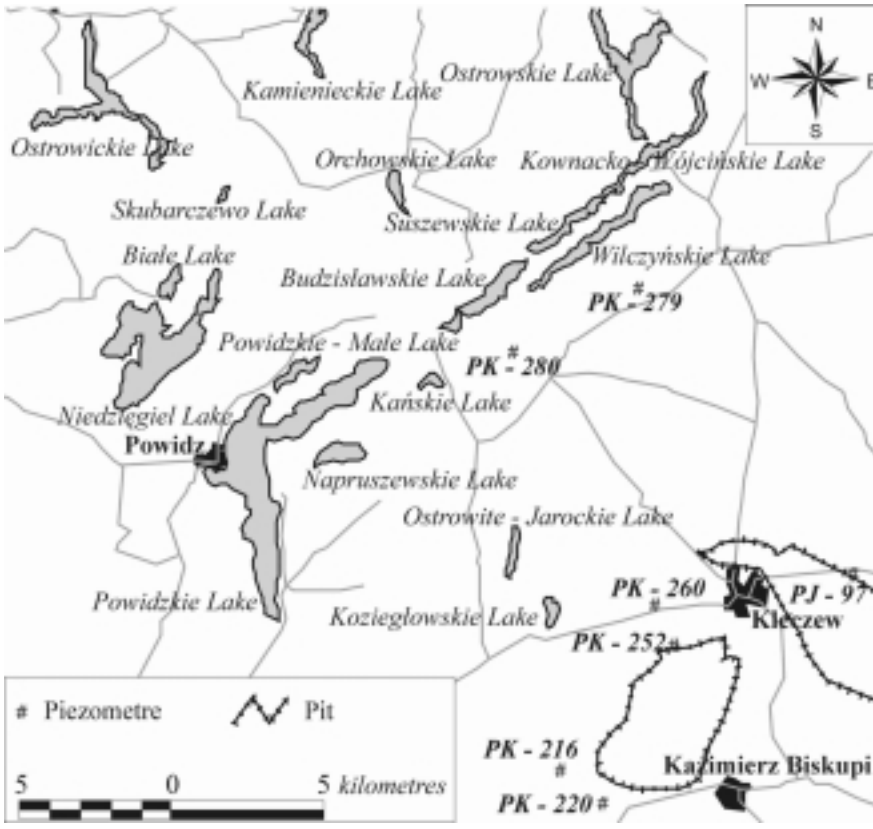

Figure 8.1. Location of opencast mine sites and lakes in the Konin region

It was considered that the common database, by its very existence, would create the basis for a meaningful discussion and ultimately lead to a consensus being reached. The INCO Copernicus Project financed by the EU 1998–2001 allowed development of a Decision Support System (DSS) in which the ground and groundwater database became the core component. Schematic representation of the DSS concept proposed by WUT is shown in Figure 8.3.

The DSS developed for the Konin region is intended not to guide statutory decisions but rather to display and help analyse the ground, water and environmental conditions. The DSS offers a number of simple 'handles' to make the analysis transparent, quick and reliable. An important component module of the DSS is the engine, enabling the user to evaluate a range of water-oriented scenarios, thereby allowing the parties to check possible effects of their future decisions.

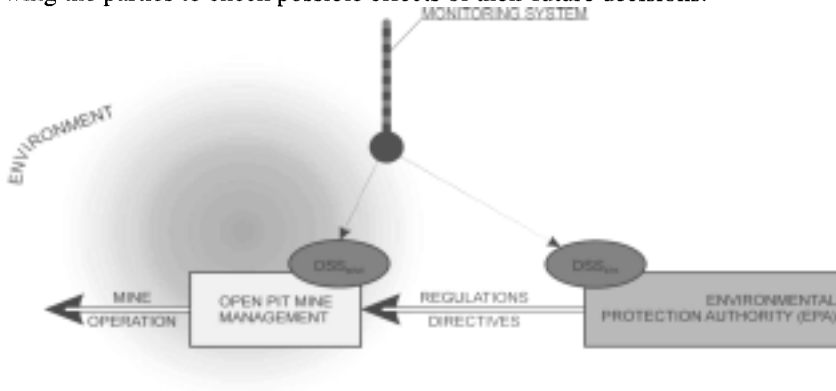

Figure 8.2. Concept of a shared database for all parties

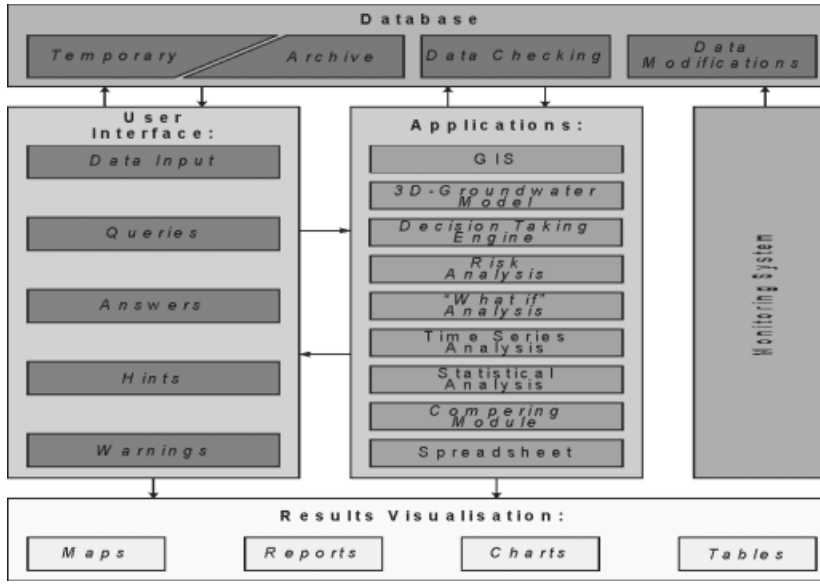

Figure 8.3. Structure of the Decision Support System

8.5 Conclusions

Having tested the DSS, the system is then passed to all parties involved in the groundwater appraisal. Assessment of the water and environmental situations in the Konin region is then left to those parties. Whenever they wish to discuss and resolve a future conflict, the agreed tool (the DSS) and the established ground profile will be available. It is thereby hoped that a consensus will be readily achieved.

Part C Model Construction and Visualisation

Subsurface geological modelling became an economic and technological reality in the late 1980's, when competing 3D geoscientific information systems were the subject of considerable research and evaluation. However the 3D model is not complete until it has a 4D aspect and includes information as to how processes develop over time. Integration of modelling within decision-support systems is now occurring, spurred by the evolution of the Internet and Web-browser technologies, hardware and software developments, expanded information transmission capabilities, data visualisation, and improved data base concepts. Despite considerable research being devoted to subsurface characterisation over the past decade, the pace of technological innovation has outstripped the ability of many potential users to evaluate and adopt promising new characterisation methods.

Geological modelling is enabled using a set of mathematical models, including topology (node connections), geometry (node locations) and feature properties (node attributes). This provides the basis for a "Shared Earth Model", a key vehicle for sharing subsurface knowledge between multi-disciplinary teams.

Often models presented at briefings and conferences appear impressive, but there is concern with the amount of skilled manpower required to create them. Many different data collection and processing methods are being applied. It is pertinent to question whether each model is equally valid, and whether there is the potential for building a more widely applicable, holistic geoscience model. It appears that the current state-of-the-art is still less than desired. Some independent means of validating a model before releasing it for wider application must be found, certainly if it is to be accepted as a core part of the decision management process. To do so will mean addressing the issues arising from use of data from different sources and the integration of data with context and judgment.

Current efforts concerning global warming and climate change may provide the driver, with the need to view the Earth as an entity, responding to one whole process. Geology has a pivotal role in dealing with the various influxes and interfaces for such a model.

The need to incorporate judgment and experience, alongside hard technical fact, points to the need for 'expert systems', but this would be a massive undertaking, and the effort in the short term may not be worthwhile.

One can take the recent example of the most understood area (geologically) in the UK – Sellafield. About £260M has been spent on ground investigation, for an area of about 60km^2. Yet a holistic view could not be obtained; even though the area became well understood, it was not fully so. A lot of geological interpretation was needed, yielding a good, but not comprehensive, model. Although a great deal of scientifically valuable information was collected, it was not all pulled together to create a single entity.

The need for validation of data is now fairly well accepted, but the similar need for models seems not yet to be recognised.

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Nevertheless there would appear to be sense in finding some independent means of validating a model before releasing it for wider application, certainly if it is to be accepted as a core part of the decision management process. To do so will mean addressing the issues arising from use of data from different sources and the integration of data with context and judgement.

Additional experiences with the 'Profile Approach' in Lower Saxony conducted by the NLfB and the BGR (national geological survey) show the effectiveness of using cross-sections, at least for traditionally trained geoscientists. But such a system on a regional scale requires an enormous database. The NLfB had some 300,000 boreholes and 1.9 million block descriptions in their database, compiled from archives collected from the 1840's to date, and provided from private companies and NLfB's own boreholes. Compilation requires substantial resources.

It is recognised that there is no single ideal tool for model construction or visualisation. Many models have already been produced, but at the moment there is no pressure to use a standard approach. Scientific expertise must be applied at all modelling stages. Existing model-building software can sometime have a steep learning curve, and although modellers can use the computer programs, geologists can often be excluded. The geologist needs to be allowed to provide data in such a way that it can be used efficiently. The work of the geoscientist does not end with the completion of the model construction. There remains the need for emphasising how the model can be useful, provide value for money and information relevant to the real world, and make the appropriate organisations aware of these capabilities.

9 Visualisation: are the images really useful?

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9.1 Introduction

For human beings vision is a most important sense. Recent medical research shows that about 50% of the brains' neurones are in some way associated with visual perception. This is why people can absorb large amounts of pictorial information so readily.

Images are therefore used in many scientific disciplines to record complex phenomena or objects. In order to avoid misconceptions, standardised schemes have been developed for recording and handling three-dimensional (3D) information in a two-dimensional (2D) way. Schemes such as geological maps, mine plans or construction drawings can be thought of as aids to building a mental model of the depicted objects. In the case of complex phenomena, 2D drawings may not always be effective and so there may be a need to supplement these with 3D images (e.g. block diagrams in geology, or explosion drawings in engineering).

The advent of the computer, and especially the cathode ray tube as an I/O device, prepared the ground for a completely new way to handle, modify, and display spatial information. Since the 1980's, scientific visualisation has been boosted by the development of increasingly powerful graphic processors, making it easier to generate charts, diagrams, 3D models, animations; even entire virtual worlds.

However, there is a danger that the actual information may be obscured by too much decoration. For geoscientists, questions arise concerning whether visualisation can play a pivotal role in the investigation of the subsurface. This is now considered, drawing examples from recent projects.

9.2 What is Visualisation?

Tufte (1990) refers to visualisation as "cognitive art". He stressed that the aim of envisioning information can only be accomplished with a graphic design that takes into account the way human perception works. Keller and Keller (1992) applied this term to "the study, development, and use of graphic representations and supporting techniques that facilitate the visual communication of knowledge". A more computer-oriented definition has been proposed in a report by the Panel on Graphics, Image Processing and Workstations of the National Science Foundation.

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According to McCormick et al. (1987) "visualisation is a method of computing. It transforms the symbolic into the geometric, enabling researchers to observe their simulations and computations. Visualisation offers a method for seeing the unseen. It enriches the process of scientific discovery and fosters profound and unexpected insights". In the context of this paper, the comprehensive definition by Keller and Keller (1992) will be adopted. Accordingly, visualisation is regarded as a subject that brings together the following disciplines:

- computer graphics
- computer-aided design
- image processing
- computer vision
- signal processing
- human computer interaction
- psychology (perception, cognition)
- ergonomics.

9.3 Geoscientific visualisation

The usefulness of images depends on the kind of information to be displayed. In general, one may distinguish the visualisation of data, shapes, volumes and processes. Due to the large variety of objects and phenomena, specific display techniques may need to be used in each field of application.

9.3.1 Data Visualisation

Graphic display of numerical data is a considerable help for revealing potential relationships. This is because the human eye and the human brain possess extraordinary capabilities for recognising patterns and shapes. In data visualisation activities, three stages can be discerned (Keller and Keller, 1992):

- exploration (search for relationships)
- analysis (study of known relationships)
- presentation (communication of results).

Exploration and analysis are parts of the model building process. Both activities have to be performed iteratively to achieve a consistent model obeying the observations (Skala and Prissang, 1999). For the presentation, the data and their interrelationships need to be portrayed in a form that can be easily understood. The approach to using imagery for display of data was developed during the second half of the 18th century (Tufte, 1983). William Playfair (1759–1823) published a number of chart types that are now considered fundamentally basic: bar charts, scattergrams, time series plots, and multivariate displays (Playfair, 1786). Modern statis-

tical packages offer further variety, e.g. pseudo-topographic surfaces, combinations of surfaces and bodies, and vector fields.

9.3.2 Shape visualisation

The basic tool for recording geological information is the geological map, a two-dimensional representation of three-dimensional features in conjunction with time (Powell, 1992). To facilitate its interpretation by a geologist, the map is accompanied by one or more sections and an explanatory booklet ('memoir') summarising the field observations and any pertinent hypotheses concerning the evolution of a mapped area. However, the geological map is not presented in a form that can be readily interpreted by non-geoscientists.

An early attempt to overcome the drawbacks of the 2D representation can be found in the oldest known, preserved geological map: the Turin Papyrus. This dates back to the reign of Ramses IV from 1163–1156 BC (Meyer, 1997). Figure 9.1 shows the central part of this map. Clearly visible are the outlines of the hills on both sides of the roads; these have been rotated into the map plane to provide an impression of the landscape. From the Middle Ages onwards, block diagrams have been used to illustrate subsurface structures.

The development of computer-aided design systems (CAD) led to a pronounced paradigm shift with the introduction of true 3D representation schemes, e.g. the Boundary Representation (although models are still viewed on a 2D monitor!). A constructed object could now be visualised and interactively modified. 2D views as seen on the monitor are no longer stored but extracted from the 3D representation held within the computer database.

The earliest applications of CAD in the geological community were orientated to the modelling of ore deposits for the mining industry (around 1980). Mining geologists were thus able to build 3D digital representations of the deposit geometry and also of the spatial distributions of relevant properties (e.g. ore grades). To facilitate exchange of models between the different specialists, the same modelling package would have to be utilised in all departments. However, dissemination of the model to outside bodies, statutory authorities or the general public, necessitated the production of pictures (usually as hardcopy, although CD presentation is becoming increasingly acceptable). Communication is now being further improved by the development of the Virtual Reality Modelling Language (VRML) and the more widespread availability of 3D browsers.

9.3.3 Volume visualisation

Property modelling is likely to require subdivision of the spatial objects into cells within which the property values will be assumed homogeneous or exhibiting a quantifiable degree of variation. Such subdivision can be carried out in a regular or a hierarchical) way. Representation schemes include among others 3D raster and octree structures. For each cell, an attribute vector is stored. The attribute val-

ues could either be measurements (e.g. seismic depth) or estimates derived from interpolation of scattered point data (e.g. mineral concentration).

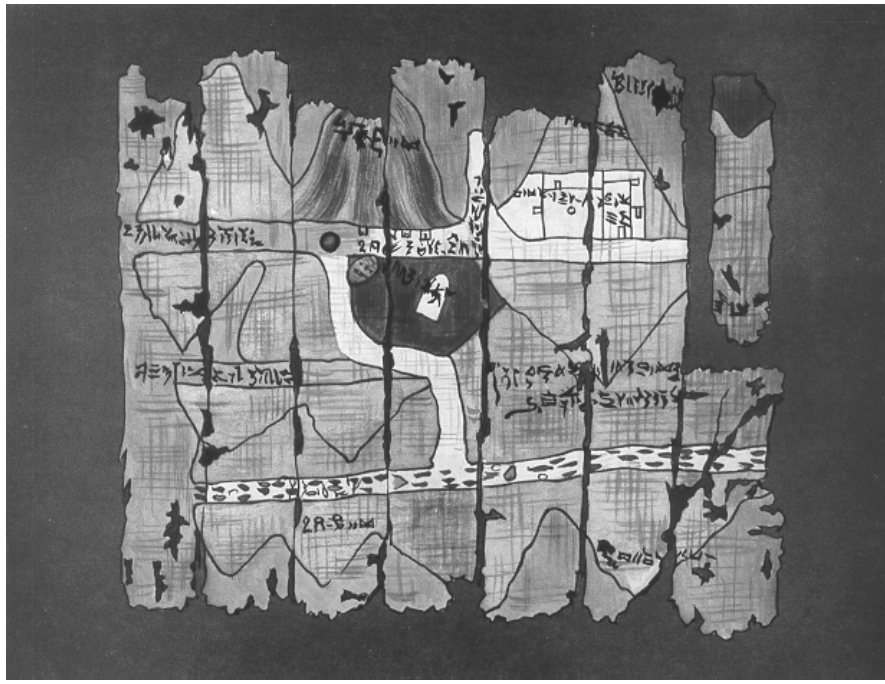

Figure 9.1. Central of the Turin Papyrus, the world's oldest geological map (from Lauffer, 1958) [© Société de l'Industrie Minérale (Paris), reprinted with kind permission of Société de l'Industrie Minérale]

The range of methods available to visualise volumes varies from package to package, and include:

- volume rendering
- colour coding
- attribute algebra
- volumetrics
- peeling
- opacity control
- isovalue surface and body generation
- clipping
- grid map extraction
- embedded geometry (i.e. the display of wireframe and Boundary Representation models)
- connected component labelling
- skeletonisation.

Data sets can be very large, and so computer processing speed is an issue, especially to execute some of the new rendering algorithms.

Although there are now a number of volume visualisation packages commercially available, a standard exchange format does not yet exist. Currently dissemination of property models is achieved by extraction of isovalue bodies or surfaces which are transformed into VRML models. By combining a number of isovalue bodies with different thresholds, an onion-peeling effect can be simulated. The user of such models is nevertheless restricted to the pre-set thresholds.

9.3.4 Process Visualisation

Processes encompass dynamic information like time-dependent measurements or the movement of groundwater. Their visualisation is computationally demanding. Time-slices can illustrate the state changes in a model by a series of still images. Animation can link these together, presenting the changes as a movie. Virtual reality adds a further step, enabling the user to interact with the visualisation, e.g. changing the viewpoint or altering model parameters. Dedicated projection hardware allows the simultaneous immersion of several people within a virtual world. A well-known example is the flight simulator whilst, in geoscience, bespoke systems have been developed for reservoir modelling and engineering.

9.4 Examples

A large scale geostatistical study of the spatial variability of ore and waste grades within the Styrian Erzberg siderite deposit, near the town of Eisenerz (Austria), showed complex variograms exhibiting anisotropies (Prissang, 1999). Each of the experimental variograms could be fitted with a nested structure consisting of a nugget effect model, an exponential model and a linear model with sill. In order to gain a better insight, the directional variograms for each investigated plane were turned into wireframe models, the variogram values acting as elevations. Using the geoscientific modelling system Surpac (Surpac Software International (Pty) Ltd., Perth, Western Australia), the wireframe models could be transformed into TIN-based digital terrain models (DTMs). Visualisation of the variograms as pseudo-topographic surfaces provided a clear view, quickly enabling recognition of the zonal anisotropy, i.e. dependence of the variogram on the direction of the sample pair vectors.

Since most software systems cannot handle a zonal anisotropy directly, it is common practice to represent it by fitting nested structures with geometric anisotropy consisting of variogram models with ranges far greater than the search radii used in subsequent estimation runs. However, such transformation:

- Is a relict from the beginning of computer applications (as it spares one coordinate transformation per structure and control point in a kriging run)

- Contradicts the fundamental scientific principle of Ockham's razor (see Jackson, this volume)
- Obscures the clarity of the theory of regionalised variables (Matheron, 1962) as sill and range ellipsoids and their orientation cannot be seen in relation to the directions of the geological processes.

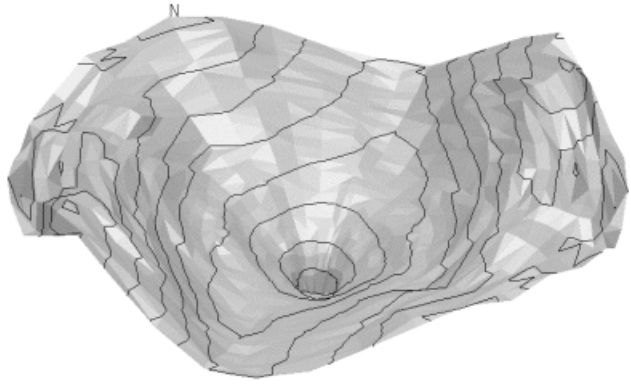

Figure 9.2. Experimental variograms for ln(SiO2) in horizontal plane (Styrian Erzberg, blasthole data) shown as pseudo-topographic surface (vertical exaggeration 300 times)

Having fitted the directional variograms with an appropriate nested structure, it was then possible to construct a range and sill ellipsoid for the exponential structure as well as for the linear structure with sill. The zonal anisotropy of a structure can be described by the model type, the sills (C_x, C_y, C_z) and ranges (r_x, r_y, r_z) along the main axes of the anisotropy ellipsoid as well as the three Euler's angles ($\bullet_Z$, $\bullet_{Y'}$, $\bullet_{X''}$) to describe the orientation of the anisotropy ellipsoid. The geostatistical routines in the Linear Octree Based Property Modelling System (Prissang, 1992) have already been changed to accept the parameters for zonal anisotropy in such a form. This approach offers two advantages: (1) the speed of geostatistical structure analysis is increased by omitting the phase requiring differential variograms to be fitted, (2) it is possible to visualise variogram values in a section through an anisotropy ellipsoid and to compare them visually with the experimental variograms.

The second example focuses on the benefits of visualisation in the context of computer-aided geometric modelling where a number of organisations are collaborating. The project concerns the assessment of the coal bed methane (CBM) potential of the Santa Terezinha coal field in the south-eastern part of the Paraná basin, Brazil. This area is characterised by the occurrence of abundant coal seams within an Early Permian succession of sandstones, mudstones, and shales. The size of the tectonic blocks was known to be an important factor for future economic production, thus a structural model had to be established. The top of the crystalline basement was selected as a reference surface. However, the drillhole data supported several hypotheses concerning the tectonic setting.

A conceptual model was then devised which did not contradict the regional geological information. A geophysical study by Padilha and Vitorello (2000) revealed that the dominant tectonic structure is a north-west plunging graben-like depression, historically known as the "Torres Syncline". This was characterised by a set of faults causing downward movement of the sediment infill. 27 sections in a NE–SW direction were constructed to model the structure. These sections gave a clear indication of steep normal faults with vertical displacements between 30 and 250 m, accompanied by relatively small horizontal displacements in the north-easterly direction. Based on this model, five tectonic "mega blocks" were delineated (Figure 9.3).

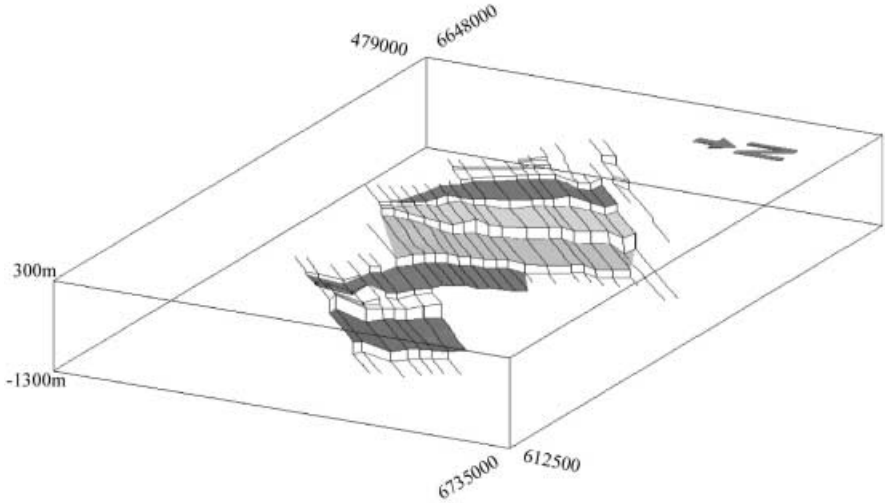

Figure 9.3. 3D view of tectonic blocks selected for initial assessment of the CBM potential in the Santa Terezinha coalfield in SE Brazil (view from NE, vertical exaggeration 15 times) (Burger *et al.*, 2001)

These blocks underwent further investigation to determine the amount as well as the properties of the coal. Finally, the in situ gas volumes could be estimated. The results showed that the Santa Terezinha coalfield could be a valuable exploration target deserving more detailed investigation (Burger et al., 2001). This modelling work was carried out jointly by two scientific working parties based at the Freie Universität, Berlin (Germany) and the Universidade Federal do Rio Grande do Sul, Porto Alegre (Brazil) in a period of about three weeks. The exchange of digital models and the use of interactive graphics enabled researchers of both groups to inspect each others results and to modify the model rapidly. Without the use of the interactive geoscientific modelling system (Surpac) by both groups and an internet connection, such a fruitful collaboration would not have been possible.

Numerical simulation of the movement of groundwater requires creation of models that comprise static components to describe the geometry and hydraulic properties of the aquifer system, together with dynamic components for simulating flow and transport processes. Such models can be very complex. According to Skala et al. (1995), such tasks can be accomplished in an efficient way by using

software packages which integrate computer-aided design, property modelling and groundwater modelling tools.

An example of this approach is the investigation of the groundwater flow regime in the Upper Messini basin (SW Peloponnesus) by Spyridonos (1994). The basin is a part of a larger tectonic structure, the Kalamata-Kyparissia graben. Its northern and eastern boundaries are formed by two fault zones. The basin is filled with post-Alpine sediments of Pliocene to Holocene age which lie above flysch sediments belonging to the Pindos and Tripolitza zones. In conjunction with their tectonic setting, the lithology of the Alpine formations has led to hydraulically closed groundwater conditions for aquifers in fractured or porous media.

There are two aquifers: one phreatic and one confined. The confining layer is a 5–20 m thick clay occurring at depths between 20 and 60 m. Surpac was again selected for the modelling since it includes the widely accepted 3D finite-difference groundwater modelling programme 'Modflow' (McDonald and Harbaugh, 1988). Thus a smooth data transfer between the graphics module, geometric and property models as well as the input and output data from Modflow could be assured.

The major factor influencing the groundwater regime is the Amfitas river. This flows through the basin in a N–S direction and forms the only outlet for the basin. The second factor is the inflow to the basin from the west: the discharge from the neighbouring Dorion basin, and from the north-east: subsurface discharge from the fault zones delimiting the basin. The third factor influencing the groundwater regime is the spatial distribution of the hydraulic conductivity, K. The values of K vary from 1×10^{-6} in the central part to 1×10^{-5} at the margins of the basin. The elevation difference between the aquifer limit and the central part of the basin is about 100–150 m, causing a gradient in the piezometric head. Because of the lower K values, the groundwater in the central part cannot flow into the river as fast as it flows in from the margins of the basin. Thus it was possible to explain the periodic flooding of the central southern region in spring, dissipating during the summer.

Despite their great potential, integrated systems have not yet attained acceptance as standard tools in ground water and environmental engineering. This situation may be attributed to the still relatively high software acquisition costs.

9.5 Caveats

The production of a 3D visualisation is not free of problems. The most important limitation is human perception due to the distance between the eyes, limiting stereoscopic vision to distances up to 500 m (Mühlfeld et al., 1981) so that visualisation of regional information requires some degree of vertical exaggeration. This can nevertheless provide a better understanding of the displayed objects, rather as a caricature accentuates characteristic features. Nevertheless, misconceptions can arise, e.g. exaggerated perception of geological dip. Interactive graphics can help avoid misinterpretation, for instance by encouraging users to inspect the model by gradually increasing vertical scale to get an impression of the displayed objects.

Other problems that concern the visualisation process:

- Most (geo)scientists do not have a formal training in visualisation
- Trial and error have to be used to arrive at an aesthetically pleasing image
- The desire to produce images close to reality may lead to incorporation of too much detail, obscuring the underlying processes
- Not recognising that both cases may drag down overall efficiency
- Not realising that visualisation requires a similar effort to set-up as does a classical geological model.

There is also an important societal impact of visualisation. Today, nearly any large scale projects has to be presented to the general public by means of 3D images or animations. There is a danger that this will focus on the outward appearance at the expense of internal quality, and may diminish the opportunity for public discussion. A further problem is that regulatory bodies may appraise the worth of the project on the basis of the quality of visualisation rather than the results of the underlying scientific or engineering work.

9.6 Conclusions

The case studies have demonstrated the advantages of visualisation but drawn attention to a number of drawbacks. Generally speaking, visualisation is useful, but only if it conveys information rather than depicting the obvious.

Geological models are never more than generalisations of reality. Currently, the tools provided by computer-based visualisation packages are rather limited. There is an outstanding need to incorporate information about uncertainty.

The value of visualisation is determined by means of cost-benefit analyses. Provided that CAD systems or computerised modelling packages are already being employed, the additional expenditures for visualisation are negligible. There are nevertheless substantial benefits:

- Better insight to the subsurface conditions
- Improved models
- More realistic predictions
- Enhanced communication with the general public
- Boost in productivity
- Better decision support.

In short, visualisation is, and will continue to be, a key issue for the geoscience community as well as in geoscience-related engineering disciplines.

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10 Numerical schemes for process simulation: software for coupling pattern recognition to process modelling

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10.1 Introduction

The coupling of software for visualisation and/or pattern recognition with software for process modelling is a most challenging task.

Many visualisation packages are based on tetrahedral cell-complexes (Paoluzzi et al., 1993). In principle, tetrahedral complexes also offer a good basis for numerical simulation of porous media flow and geomechanical behaviour (Trykozko, 1997). One of the complications that arises from such a coupling is the difference in scale between the resolution of the visualisation tools and those employed by the process modelling software. To handle any mismatch requires a numerical method to homogenise the absolute process parameters such as relative permeability, capillary pressure, rigidity and creep viscosity. This has been attempted for porous media by developing a finite element code.

The basis of the new code is to develop upper and lower bound methods to assess *a posteriori* error bounds. The software is based on tetrahedral cell-complexes upon which discrete analogues of the flow equations may be solved. Numerical homogenisation is seen from a broader perspective, focussing on the more general problem of coupling visualisation software with process simulation software.

The finite element method utilises the idea originally developed for computational electromagnetism (Bossavit, 1998). This initially considers two equations: the 'div-side' equation for the scalar potential (e.g. pressure, piezometric head) and the 'curl-side' equation for the vector potential (e.g. stream function). It is thus possible to locate Nawalany's 'velocity oriented approach' (Nawalany, 1986; Zijl and Nawalany, 1993) in the context of mainstream finite elements. It turns out that all finite element methods based on the curl-side equation are 'velocity oriented', thus countering the most important argument for choosing finite difference models (such as Modflow or Eclipse) as opposed to finite element models.

The classical conformal-nodal finite element method (CN-FEM) for the scalar potential in porous media flow is well known (Strang and Fix, 1973); the node-based method for the displacement is its analogue in geomechanics (Zienkewicz and Taylor, 1967). Such methods are upper bound methods; they over-estimate the

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homogenised mobility (in porous media flow), rigidity (in elasticity) or viscosity (in creep flow).

The mixed-hybrid finite element method (MH-FEM) is less popular, but nevertheless counts as a standard methods (Brezzi and Fortin, 1991; Chavent and Jaffré, 1986; Kaasschieter and Huijben, 1992; Raviart and Thomas, 1977; Trykozko et al., 2001; Weiser and Wheeler, 1988). One of its most important features is its lower bound property. It is supposed that CN-FEM is already familiar to the reader but MH-FEM is now introduced, utilising the relatively new edge element method for the vector potential. Bilateral error bounds have been described by Trykozko (1991), whereas a rigorous proof of the error bound property is presented by Trykozko et al. (2001).

10.2 Cell complexes and their properties

Topology deals with properties that endure whilst geometrical figures are transformed continuously. Metric properties such as the distance between a pair of points may change, but the number of points and their relative orientations may not. As an illustration, consider 4D space-time. It is known from the theory of general relativity that its metric is dependent on the presence of matter. However, it is still an open question whether its topology is matter-dependent too. As Goedel pointed out, confirmed by Einstein, a matter-dependent topology allows one to travel into temporal regions of the universe that have already been passed. In this paper Whitehead's topological priority above matter has been adopted, and it is accepted that the universe's events cannot be repeated (Tanaka, 1985). As a consequence, 'the arrow of time' $t > 0$ is accepted when handling time-dependent process equations.

A cell is one of the simplest possible topological objects; it is any figure that is topologically equivalent to a ball. The topological properties of a ball are: (1) it occurs as one piece (i.e. any attempt to divide the ball into more than one piece would require cutting, and that is forbidden in a continuous transformation), and (2) it neither loops (so it is not torus-like) nor contains holes (so it has one boundary) (Henle, 1979). Here it is considered that cells may be glued/pasted together along their faces. This way it is possible to form simple cell-complexes (in 3D these would be simple points, straight lines, flat faces or volumes). In principle, a simple cell-complex may be built up from any regular polyhedron, but this discussion is here limited to tetrahedral cell-complexes since these are used in many visualisation packages and form the simplest possible mesh for a finite element approach. However, the cube is important too, since it forms the 'grid-blocks' of the popular control volume finite difference method.

First consider the example, of a cell-complex set up as a division of the modelling domain into N cubes that are divided into five tetrahedra. The modelling domain is assumed to a cube too, so it is possible to assume periodicity: i.e. count equivalent nodes on two opposite boundaries only once. There will then be N 'active nodes' and $T = 5N$ tetrahedra. Since there are four faces for each tetrahe-

dron, shared by two, there are $F = 10N$ active faces (triangles). Thus from the Euler-Poincaré formula $N - E + F - T = \chi$, where $\chi = 1$ for simply connected domains [Weintraub, 1977], it follows that there are $E = 6N - 1$ active edges [Henle, 1979; Bossavit, 1998]. In a similar way it is possible to derive a division of the cubes into six tetrahedra, leading to $T = 6N$, $F = 12N$ and $E = 7N - 1$. Looking at these numbers, the first thought is that numerical models based on nodes as degrees of freedom (e.g. CN-FEM) are quickest with respect to computer time and memory requirements. The second-cheapest method would be based on edges, whereas the most computationally intensive methods would be based on faces (e.g. MH-FEM). Of course, tetrahedral cell-complexes may have a much more general and 'irregular' character. For instance, they may be obtained from alpha complexes, originally developed for visualisation and pattern recognition (Gerritsen et al., 2001a, 2001b).

10.3 Process modelling

The new approach to process modelling contains the concepts of (1) incidence and (2) orientation. Each edge has a 'forward direction' from which each face has a notion of 'turning clockwise', thus each tetrahedron has its own 'corkscrew rule'. Even nodes are oriented, shown by attributing a sign, + or – (Paoluzzi, 1993).

Two simplices, σ and s, can be assigned, of dimensions d and $d+1$ respectively. The incidence number will be: ± 1 if σ is a face of s, or 0 otherwise. The sign, + or –, depends on whether the orientations match or not. Gathering the incidence numbers in arrays leads to three matrices: (1) the $T \times F$ matrix D, (2) the $F \times E$ matrix R and (3) the $E \times N$ matrix G (Henle, 1979; Bossavit, 1998). These incidence matrices have an appealing meaning: D, R, G are the discrete counterparts of the spatial differential operators div, rot, grad upon which the process models are based. Indeed, for topological 'balls' $\mathrm{DR} \equiv 0$ and $\mathrm{RG} \equiv 0$, which are the discrete analogues of the well-known relations $\mathrm{div}(\mathrm{rot}.) \equiv 0$ and $\mathrm{rot}(\mathrm{grad}.) \equiv \underline{0}$. However, in contrast to the partial differential operators, the incidence matrices are metric-free, i.e. depend only on topology of the cell-complex, offering a major advantage regarding the assumed topological priority over matter.

The duality of meshes also plays an important role in process modelling. For a tetrahedral primal mesh, the dual mesh is such that the barycentres of the tetrahedra of the primal mesh correspond to the nodes of the dual mesh, whereas the faces (triangles) of the primal mesh correspond with the edges of the dual mesh, and so on (Figure 10.1). More specifically, a dual edge $\hat{e}$ belonging to primal face f is the union of the two line segments that join the barycentre of that face with the two barycentres of the tetrahedra flanking that face. The dual mesh is not a simple mesh, since the edges are *broken* lines.

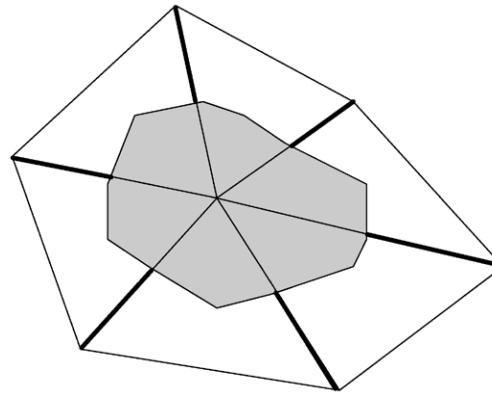

Figure 10.1. The dual mesh (after Bossavit, 1998)

10.4 Paradigms

The line of thought can be expressed using the following equations as paradigmatic 'first principles':

$$\mathrm{div}(\underline{\underline{\lambda}} \bullet \mathrm{grad}\,\varphi) = 0 \text{ in } C \qquad [1]$$

$$\mathrm{rot}(\underline{\underline{\lambda}}^{-1} \bullet \mathrm{rot}\,\underline{a}) = \underline{0} \text{ in } C \qquad [2]$$

Both [1] and [2] describe steady single-phase fluid flow in a domain C filled with porous material. 'Div-side' equation [1] is well known in groundwater hydrology and petroleum reservoir engineering. Although 'curl-side' equation [2] is well known in the theory of electromagnetism (Maxwell presented his famous equations using a vector potential [Bossavit, 1998]), this equation is hardly known in the context of porous media flow. It is our strong conviction that [2] is extremely useful. Therefore attention will be focused on [2], while supposing that [1] and its discrete analogues are already familiar to the reader. Here $\underline{\underline{\lambda}}$ $\{\mathrm{m^2.Pa^{-1}.s^{-1}}\}$ is the mobility tensor (the intrinsic permeability divided by the viscosity), φ $\{\mathrm{Pa}\}$ is the (scalar) potential, and $\underline{a}$ $\{\mathrm{m^2.s^{-1}}\}$ is the vector potential.

The (scalar) potential equals the fluid pressure minus the hydrostatic pressure. Consider groundwater with a density of $1000\,\mathrm{kg.m^{-3}}$ in a gravitational field of $10\,\mathrm{m.s^{-2}}$. A piezometric height of $1\,\mathrm{m}$ then corresponds to a water pressure of $1\,\mathrm{dbar} = 10{,}000\,\mathrm{Pa}$. In other words, the numerical value of the piezometric head may be equated to that of the potential, expressed in decibars. Similarly, the mobility may be equated to the hydraulic conductivity. However, for oil, which has a different density, this approach would not be valid.

In contrast to what is generally believed, the vector potential also has a physical meaning. In a plane normal to its direction, the stream function will equal its abso-

lute value multiplied by a metric coefficient. The flux density $\{ \mathrm{m.s^{-1}} \}$ (i.e. the specific discharge) is then given by $\underline{q} = \mathrm{rot}\, \underline{a} = -\underline{\underline{\lambda}} \bullet \mathrm{grad}\, \varphi$.

Equations [1] and [2] can be extended to describe steady multi-phase flow. In the numerical example that follows, attention is focused on two-phase flow (Zijl and Trykozko, 2002). Extensions to elastic geomechanics and creep of viscous rock layers may also be possible. Although [1] and [2] are mathematically equivalent, their discrete analogues are not. This gives rise to two different numerical approximation methods, which can be used to establish error bounds. Numerical examples of the error bounds are presented next, but the theory is described by Trykozko et al. (2001).

10.5 Discrete analogues of the paradigm equations

10.5.1 The curl side

Assign to each face f of the tetrahedral primal mesh a flux $q_f = \iint_f \underline{q} \bullet \underline{\nu}_f dS$ $\{ \mathrm{m^3.day^{-1}} \}$ through that face. Denote by q the array of face-based fluxes and consider the following linear system:

$$\mathrm{D\,q} = 0 \qquad [3]$$

System [3] is equivalent to $\sum_f q_f = 0$, where the summation is over the four faces of a tetrahedron. Hence [3] expresses mass conservation for each tetrahedron.

Assign a potential difference $h_f = \int_{\hat{e}} \underline{h} \bullet \underline{\tau}_{\hat{e}}\, d\hat{\lambda}$ { dbar } along each dual edge $\hat{e}$.

Let h be the column array of face-based potential differences, then the system:

$$\mathrm{R}^T\,\mathrm{h} = 0 \qquad [4]$$

is equivalent to $\sum_{\hat{e}} h_f = 0$, which means that the circulation of $\underline{h}$ is zero along the edges of a dual face, from which it follows that $\underline{h} = -\mathrm{grad}\, \varphi$ along the edges of each dual face [Bossavit, 1998].

Equations [3] and [4] are metric-free; only the topology of the mesh matters. The metric is considered by the discrete analogue of Darcy's law:

$$\mathrm{q} = \mathrm{L\,h} \qquad [5]$$

The square $F \times F$ matrix L $\{ \mathrm{m^3.Pa^{-1}.s^{-1}} \}$ may then be constructed using a control volume finite difference approach (Bossavit, 1999), but in the context of finite elements L is obtained by the Galerkin approach (Bossavit, 1998):

$$[\mathrm{L}^{-1}]_{ij} = \iiint_C \underline{w}_i \bullet \underline{\underline{\lambda}}^{-1} \bullet \underline{w}_j dV \qquad [6]$$

where the mobility $\underline{\underline{\lambda}}$ is a tetrahedron-wise constant. The vector function $\underline{w}_e$ is defined as

$$\underline{w}_e = w_m \mathrm{grad}\, w_n - w_n \mathrm{grad}\, w_m \qquad [7]$$

where edge e points from node m to node n. Scalar function w_n is the well-known continuous piecewise linear 'hat' function. This is equal to 1 at node n, and to 0 at other nodes. Since the mobility $\underline{\underline{\lambda}}$ is a symmetrical and strictly positive definite tensor, the matrix L is also symmetric and strictly positive definite.

Combining [4] and [5] using [6] leads to the algebraic system:

$$\mathrm{R}^T \mathrm{L}^{-1} \mathrm{q} = 0 \qquad [8]$$

To transform system [8] to a solvable $E \times E$ system, the relation $\mathrm{D}\,\mathrm{R} \equiv 0$ is invoked. Writing this relation as $\mathrm{D}(\mathrm{R}\,\mathrm{a}) \equiv 0$, and recalling that $\mathrm{D}\,\mathrm{q} \equiv 0$, suggests the introduction of an array a of edge-based degrees of freedom a_e such that $\mathrm{q} = \mathrm{R}\,\mathrm{a}$. In such a way the discrete analogue of $\underline{q} = \mathrm{rot}\,\underline{a}$ can be obtained. Here $a_e = \int_e \underline{a} \bullet \underline{\tau}_e \, d\lambda$ $\{ \mathrm{m}^3.\mathrm{day}^{-1} \}$ is the tangential component of the vector potential integrated over primal edge e. Moreover, $q_f = \sum_e a_e$, meaning that the circulation of $\underline{a} \bullet \underline{\tau}$ along the edges of a primal face is equal to the flux through that face. This finally leads to the algebraic system:

$$\mathrm{R}^T \mathrm{L}^{-1} \mathrm{R}\,\mathrm{a} = 0 \qquad [9]$$

of which the $E \times E$ matrix $\mathrm{R}^T \mathrm{L}^{-1} \mathrm{R}$ is sparse and symmetrical. System [9] is the discrete analogue of [2].

Since in [1] and [9] there is no requirement for $\mathrm{div}\,\underline{a}$, physical boundary conditions can be inserted (Bossavit, 1998). The resulting system has a positive semi-definite matrix with null space containing the range of G (i.e. the solution $\underline{a}$ is unique up to an arbitrary function $\mathrm{grad}\,f$). This system can be solved using a conventional preconditioned conjugate gradient method (Bossavit, 1998; Kaasschieter, 1988; Meijerink and Van der Vorst, 1977).

10.5.2 The div side

Using a similar line of reasoning, the discrete analogue of [1] yields the system of equations:

$$\mathrm{G}^T \mathrm{L}^* \mathrm{G}\,\mathrm{p}^* = 0 \qquad [10]$$

where p^* is the array of node-based scalar potentials and

$[\mathrm{G}^T \mathrm{L}^* \mathrm{G}]_{ij} = \iiint_C \mathrm{grad}\, w_i \bullet \underline{\underline{\lambda}} \bullet \mathrm{grad}\, w_j dV$ is the well-known $N \times N$ system matrix that belongs to the 'classical' conformal-nodal finite element method (CN-FEM) (Strang and Fix, 1997; Zienkewicz and Taylor, 1967). It may be noted that G^T is the discrete analogue of the divergence in the dual mesh. In other words, system [10] is equivalent to $\sum_{\}} q_{\}} = 0$, summing over the faces $\}$ of a dual volume. Hence [10] expresses mass conservation for each dual volume (Figure 10.1).

Systems [9] and [10] are complementary in the sense that system [9] gives lower bounds for the eigenvalues of the numerically approximated coarse-scale mobility, while system [10] gives upper bounds (Trykozko et al., 2001).

10.6 Discrete flux-based process models

Computational electromagnetics employ edge elements for the vector potential. With respect to porous media flow, the flux density (or friction in geotechnics) are considered to be the standard alternative to the 'classical' potentials (of pressure and piezometric head). In contrast, node elements have a long history and so are well established. Edge elements are relatively new and have not (yet) found acceptance within the earth sciences. This is the reason for developing node-based methods for describing the flux density.

The simplest concept is to derive 'div-side' equations for the flux density. Taking the curl of [2], and using the relation $\mathrm{rot}(\mathrm{rot}.) = \mathrm{grad}(\mathrm{div}.) - \mathrm{div}(\mathrm{grad}.)$ yields $\mathrm{div}(\lambda^{-1}\,\mathrm{grad}\,q_i) + \mathrm{div}(q_i\,\mathrm{grad}\,\lambda^{-1}) - \partial_i(\underline{q} \bullet \mathrm{grad}\,\lambda^{-1}) = 0$ for any isotropic medium. If perfect layering is assumed, e.g., $\lambda = \lambda(z)$, an equation for q_z can be found that has comparable simplicity to [1]:

$$\mathrm{div}(\lambda^{-1}\mathrm{grad}\,q_z) = 0 \text{ in } C \qquad [11a]$$

As before, assuming that the medium is perfectly layered and taking the x and y derivatives of [1] will yield:

$$\mathrm{div}(\lambda\,\mathrm{grad}\,h_x) = 0,\ \mathrm{div}(\lambda\,\mathrm{grad}\,h_y) = 0 \text{ in } C \qquad [11b,c]$$

Equations [11b,c] are a special case of div-side equation [1], whereas [11a] is a special case of curl-side equation [2] in div-side disguise. The numerical solution of these equations leads to a complementary algebraic system and so to *a posteriori* error bounds. Instead of solving the relatively complicated equations [1], [2], a simpler way to solve their equivalents [11] using the established node-based finite elements method has been accomplished by Nawalany (1986). In addition, [11] forms the basis of a practical engineering result: the calculation of vertical flux density from solutions to the Dupuit approximation in aquifers, and subsequent upscaling to obtain aquifer transmissivity (Zijl and Nawalany, 1993).

The mixed hybrid finite element method (MH-FEM) provides an alternative curl-side method that is not based on the vector potential. Using the identity $\mathrm{R}^T\mathrm{D}^T \equiv 0$ – the discrete analogue of $\mathrm{rot}(\mathrm{grad}.) \equiv 0$ in the dual mesh – [4] yields:

$$\mathrm{h} = \mathrm{D}^T\,\mathrm{p} \qquad [12]$$

where p is the array of discrete scalar potentials p_t at the dual nodes (the barycentres of the tetrahedra). In this way, equations [3] and [5] yield the mixed system (Trykozko et al., 2001):

$$\begin{pmatrix} \mathrm{L}^{-1} & \mathrm{D}^T \\ \mathrm{D} & 0 \end{pmatrix} \bullet \begin{pmatrix} \mathrm{q} \\ \mathrm{p} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \qquad [13]$$

Left multiplying the upper equations of [13] by R^T and using [4] and [12] yields [8] and, hence, [9]. Moreover, since the null space of R^T is the range of D^T, the inverse procedure, starting with [8] and ending up with [13], is also possible. Hence the two systems [9] and [13] are algebraically equivalent. Since it is relatively simple to prove the convergence of [9], the algebraic equivalence is a much simpler proof of convergence of the mixed (and mixed-hybrid, see below) method than presented in the literature (Bossavit, 1998).

Since mixed system [13] has poor algebraic properties, the now classical move to the mixed-hybrid approach has been applied. Hybridisation of [13] has been described extensively in the literature (Chavent and Jaffré, 1986; Kaasschieter and Huijben, 1992; Raviart and Thomas, 1977; Trykozko et al., 2001; Weiser and Wheeler, 1988). The procedure is only briefly summarised here. First q and h are doubled such that there are two distinct values on the sides of each face. This leads to a redefinition of q, h, L, D, R, denoted here as q', h', L', D', R'. This step may be considered as a domain decomposition technique for each tetrahedron. The constraint $Mq' = 0$ expresses the continuity of normal fluxes on all faces, where matrix M has a simple structure. Constraints are introduced using a face-based Lagrange multiplier array λ. The Lagrange multiplier of each face represents the potential difference between the two adjacent dual nodes. Although the meaning of q' and h' has changed, this yields a new, but algebraically equivalent, version of [9] and [13]:

$$\begin{pmatrix} -L'^{-1} & D'^T & M^T \\ D' & 0 & 0 \\ M & 0 & 0 \end{pmatrix} \bullet \begin{pmatrix} q' \\ p \\ \lambda \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \qquad [14]$$

Since L' is block-diagonal, q' can be eliminated. Thus a symmetrical system is derived in terms of p and λ. Eliminating p leads to an $F \times F$ system in terms of just λ:

$$M[L' - L'D'^T \Lambda^{-1} D'L']M^T\lambda = 0 \qquad [15]$$

where $\Lambda = D'L'D'^T$ (Kaasschieter and Huijben, 1992, Trykozko et al., 2001). System [15] may be considered to be a preconditioned version of the algebraically equivalent systems [9], [13] and [14]. If mobility tensor $\underline{\underline{\lambda}}$ is diagonal, the matrix Λ is also diagonal. This observation leads to the famous proof that block-centred finite differences are nothing but a special case of mixed-hybrid finite elements (Weiser and Wheeler, 1988).

10.7 Numerical example: homogenisation of flow parameters

Consider an isotropic porous medium with absolute permeability $k(\underline{x}) = \zeta(\underline{x})\times 10^{-3}$ μm^2 ($1\mu m^2 = 1013.250$ mD), where $\zeta(x,y,z) = 8\mu^{-1}\alpha\beta\gamma \cosh^2 x \cos^2 y \cosh^2 z$ in the domain $|x|\le\alpha$, $|y|\le\beta$, $|z|\le\gamma$. Outside this domain the function $\zeta(\underline{x})$ is continued periodically. The factor $\mu = (\alpha+\frac{1}{2}\sinh 2\alpha)\ (\beta+\frac{1}{2}\sin 2\beta)\ (\gamma+\frac{1}{2}\sinh 2\gamma)$ is such that $\langle\zeta\rangle = 1$ and $\langle\zeta^{-1}\rangle = 8^{-1}(\alpha\beta\gamma)^{-2}\mu\tanh\alpha\tan\beta\tanh\gamma$. In the examples chosen, $\alpha=\gamma=49/50$ and $\beta = 49\pi/100$.

The water has viscosity $\eta_1 = 5\times 10^{-4}$ Pa.s = 0.5 cp, whereas the oil has viscosity $\eta_2 = 5\times 10^{-2}$ Pa.s = 50 cp. The relative permeabilities are $r_1(s_1) = \frac{2}{3}(s_1^{2\zeta(\underline{x})} - (\frac{1}{10})^{2\zeta(\underline{x})})$ and $r_2(s_2) = \frac{8}{7}(s_2^{2\zeta(\underline{x})} - (\frac{1}{5})^{2\zeta(\underline{x})})$. The capillary pressure is given by $p(\underline{x},s_1)/p_0 = b\tan((9-20s_1)\pi/14) + d(\underline{x})$ (p_0 = 1 kPa = 0.1450377 psi) where either $b=0$ and d is constant (the no-capillary gradient case) or $b=1$ and $d(\underline{x}) = 5\zeta(\underline{x})^{-1}/2$ (the saturation-dependent capillary case). The admissible interval for the water saturation is $1/10\le s_1\le 4/5$; the residual oil saturation is 1/5 and the maximum oil saturation is 9/10. In this example the exact coarse-scale absolute permeability $\underline{\underline{K}}$ is given by the diagonal matrix $\mathrm{diag}(K_{xx},K_{yy},K_{zz}) = \mathrm{diag}(F_x,F_y,F_z)\times 10^{-3}$ $\mu m^2.Pa^{-1}.s^{-1}$, where $F_x = 2\alpha^2\coth\alpha/(\alpha+\frac{\sinh 2\alpha}{2})$, $F_y = 2\beta^2\cot\beta/(\beta+\frac{\sin 2\beta}{2})$ and $F_z = 2\gamma^2\coth\gamma/(\gamma+\frac{\sinh 2\gamma}{2})$ (Trykozko et al., 2001; Zijl and Trykozko, 2001). Using the finite element analogues, where the fine-scale mobility is tetrahedron-wise constant, the fine-scale mobility using the above expressions in its barycentre is assigned to each tetrahedron.

In order to perform the numerical experiments, the following nine values of ν have been specified: 0.0001, 0.0003, 0.001, 0.01, 0.1, 1, 10, 100, 300. The bisection method (Press et al., 1986) is used with termination criterion $|r_2(s_2)/r_1(s_1) - \nu| \le 10^{-8}$ yielding the coarse-scale saturations s_β for each specified ν from which the corresponding mobilities are calculated. To solve the saturation-dependent capillary case, the saturations obtained from the no-capillary-gradient case have been chosen as initial values for the successive iteration procedure. The results obtained for the saturation-dependent capillary pressure are shown in Figures 10.2 to 10.4.

Since there is now access to two algebraically different approximation methods, there is a temptation to compare their behaviour. Thus, a set of computational experiments has been performed aiming to study the two approximate solutions. Only the parameter value $\nu = 0.1$ has been chosen for this purpose. The computa-

tions were performed for a sequence of uniformly refined meshes. The results are summarised in Figures 10.5 to 10.7.

The two methods provide solutions that are very close to each other. In general, the differences in the *yy* component between two solutions are greater. This is due to the form of the fine-scale absolute permeability, which steeply descends to zero near the *y*-boundaries.

The function describing the absolute fine-scale permeability is continuous, whereas the two finite-element methods use tetrahedron-wise constant fine-scale mobility values. Thus for each mesh in the sequence used, another discrete problem is derived from the continuous problem. For each problem in the sequence of discrete problems, the CN-FEM and MH-FEM solutions represent respectively the upper and lower bounds, although the CN-FEM and MH-FEM solutions presented do not bound the exact solution of the continuous problem.

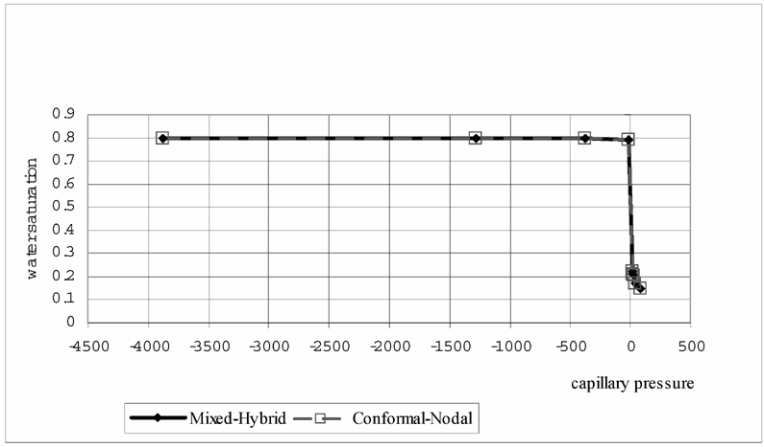

Figure 10.2. Coarse-scale water saturation S_1 vs. coarse-scale capillary pressure P

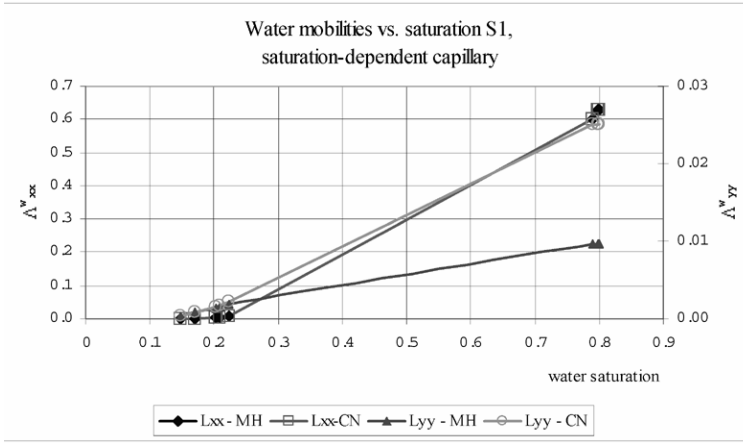

Figure 10.3. Coarse-scale water mobility Λ_{ij}^{w} vs. coarse-scale water saturation S_1

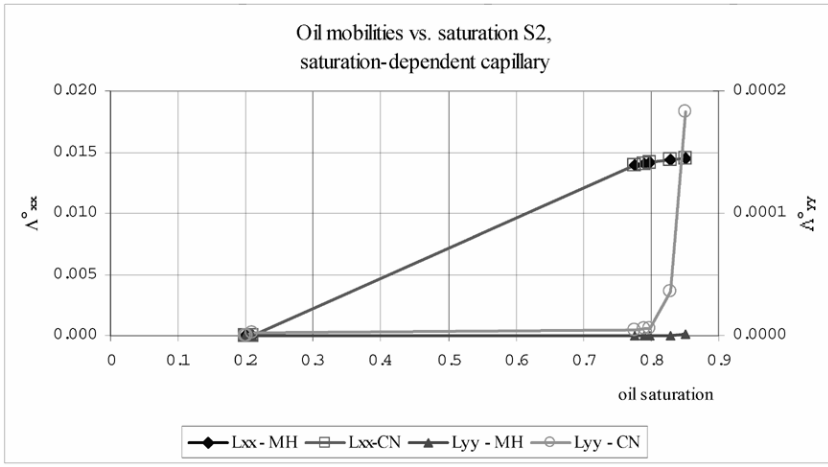

Figure 10.4. Coarse-scale oil mobility Λ^o_{ij} vs. coarse-scale oil saturation S_2

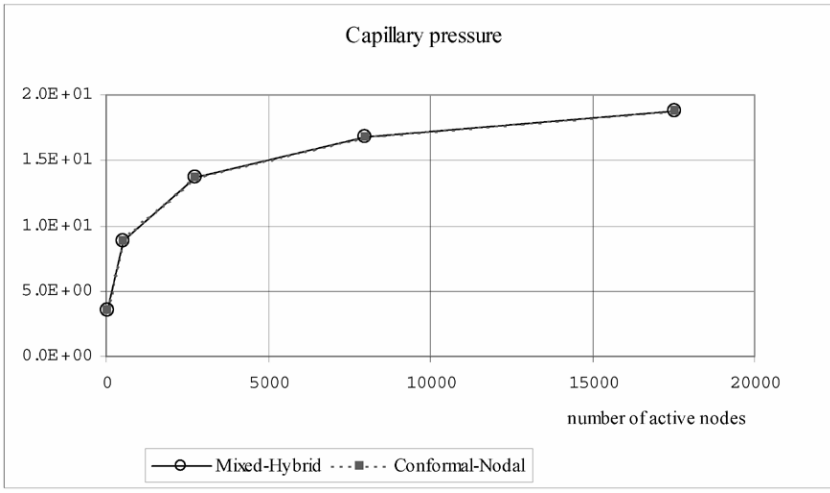

Figure 10.5. Coarse-scale capillary pressure vs. number of active nodes

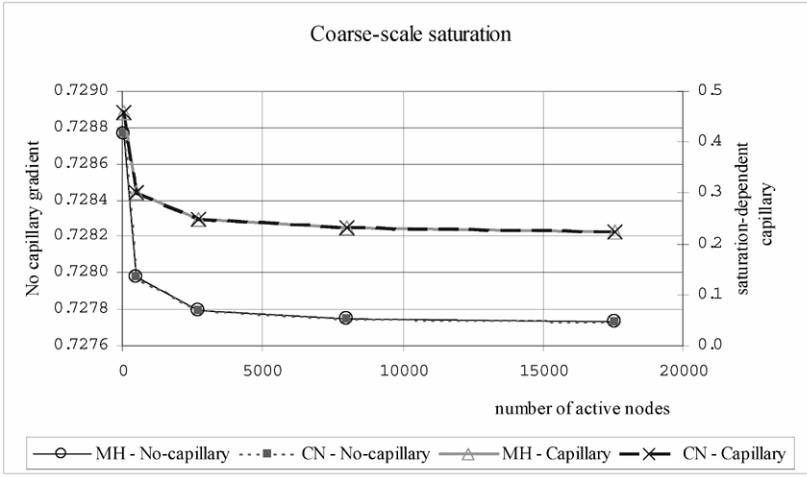

Figure 10.6. Coarse-scale water saturation vs. number of active nodes

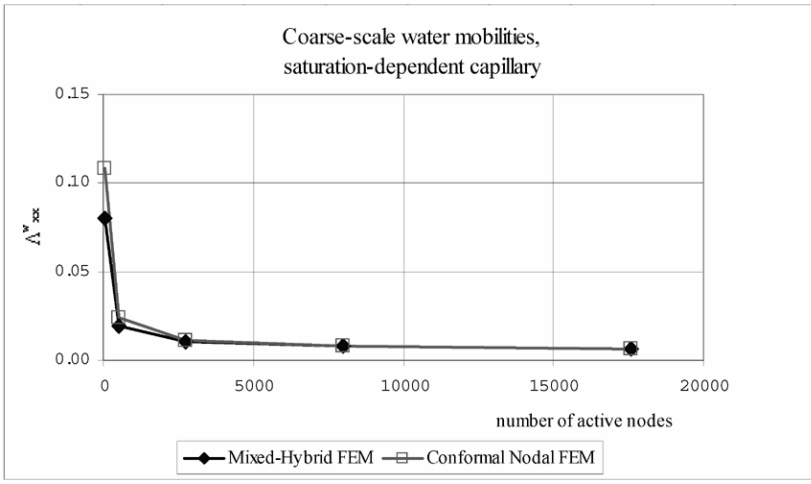

Figure 10.7. Saturation-dependent capillary: coarse-scale water mobility Λ^{w}_{xx} vs. number of active nodes

10.8 Conclusions

It has been shown that tetrahedral cell-complexes are not only useful for visualisation and pattern recognition, but also for process modelling. The essential jump from cell-complex to process simulation is bridged by the application of equiva-

lence between the three incidence matrices of a cell-complex with the three spatial differential operators from process models. Considering two mathematically equivalent process equations – the 'div-side' and the 'curl-side' equation – as 'first principles', it has been possible to derive the well-known conformal-nodal finite element method (CN-FEM), as well as a realm of algebraically equivalent complementary finite element methods that are not algebraically equivalent to CN-FEM.

The mixed-hybrid finite element method (MH-FEM) is the most popular complementary method, but the newer edge element method shows considerable promise and deserves further research. Arguments have been presented showing that CN-FEM combined with edge elements may be considered as a generalisation of Nawalany and Zijl's velocity-oriented finite elements. The div-side equations have been solved numerically to determine upper bounds, whilst the 'curl side' equations have been used to compute lower bounds. Homogenisation of two-phase flow parameters has been presented as a numerical example.

Future research could focus on building a relatively simple, hence fast, process model for visualisation and pattern recognition. This software could be based on tetrahedral cell-complexes, readily accomplished using the incidence matrices and [6]. To make the models faster, data reduction by numerical homogenisation could be utilised.

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11 Regional subsurface models and their practical usage

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11.1 The Context

Until 1998, the Geological Survey of Lower Saxony (NLfB) compiled and published regional geological maps at a scale of 1:25,000. These described the geological strata occurring at a depth of 2 m as cross sections in two directions (one of which is shown as an example in Figure 11.1) and as contours of thickness for each layer (Figure 11.2) so as to reveal the 3D subsurface condition.

Digital data processing methods have subsequently enabled the NLfB construct 3D subsurface models of the ground profile down to several tens of metres based on the 1:25,000 mapping. These models reveal the stratigraphic units by integrating the 3D subsurface models within a Geographical Information System (GIS).

11.2 Modelling methods

The modelling is achieved by calculating the lower bound of each layer using the elevation from a Digital Terrain Model (DTM). The cloud of points creates the base for interpolating using a triangulation that can be interactively changed. Editing is necessary to eliminate triangles that lie outside the lateral boundaries (Figure 11.3). The triangulation is then projected to a C1-surface and the elevation values stored as a grid, repeating the process for all layers to build the first model.

Using this model, automatically constructed cross sections can be computed to facilitate checking concepts; cross sections are very important for detecting implausible areas. Corrections may then be applied and the model recalculated. Normally three to four iterations are needed to complete the geological model.

11.3 Boundary conditions

The model consists of a number of grid files, as many as there are geological layers plus a grid for the digital elevation model of the land surface. A grid for the

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water table as well as grids for other planes, e.g. faults, may supplement these. A separate file defines the succession of grid files, i.e. the succession of geological layers. Attribute data, for example stratigraphic information, lithological descriptions, geotechnical and hydrogeological parameter values, can be placed in tables and linked to the spatial data.

Such a model of geological units permits a variety of applications:

- Prediction of ground profile prior to drilling (Figure 11.4)
- Preparation of cross sections between any selected points, straight or zig-zag (Figure 11.5)
- Mapping the distribution of any given geological formation, its thickness or depth (Figure 11.6)
- Portrayal of aquifers together with any cover layer which might protect the aquifer from pollution (Figure 11.7)
- Alternative portrayals of the geology (Figure 11.8), for instance simultaneous plotting of contour lines to delineate the morphology of the older subsurface bedrock; colours can indicate the different types of sediment
- Graphical presentations of selected aspects, from any perspective, helpful for those unfamiliar with national cartographic conventions (Figure 11.9).

The users of subsurface models are more interested in the analytical results than in the internal structure of the data or the modelling process itself. The subsurface models can be explored using the VirGIL system, a software product especially developed for regional geological applications. The VirGIL system is an extension to the ArcView GIS, utilising the components of ArcView for graphical presentation and processing. The outcome is in the form of ArcView themes; non-geological users readily accept such models.

11.4 Outlook

Dividing the modelling process into two operations – constructing the map and building the digital model – has enabled correction of the geological base information. The digital model is able to support fieldwork and assist the evaluation of borehole logs as well as deliver digital models of even higher quality.

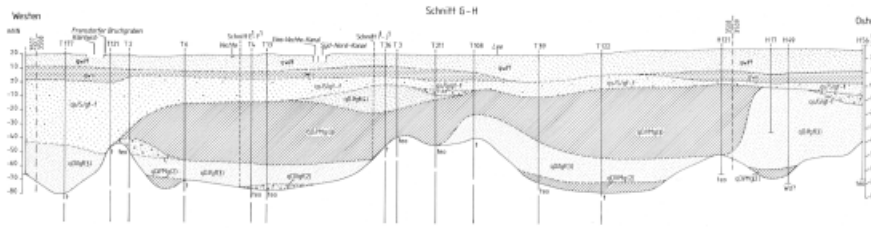

Figure 11.1. One cross section as an example (Nordhorn area)

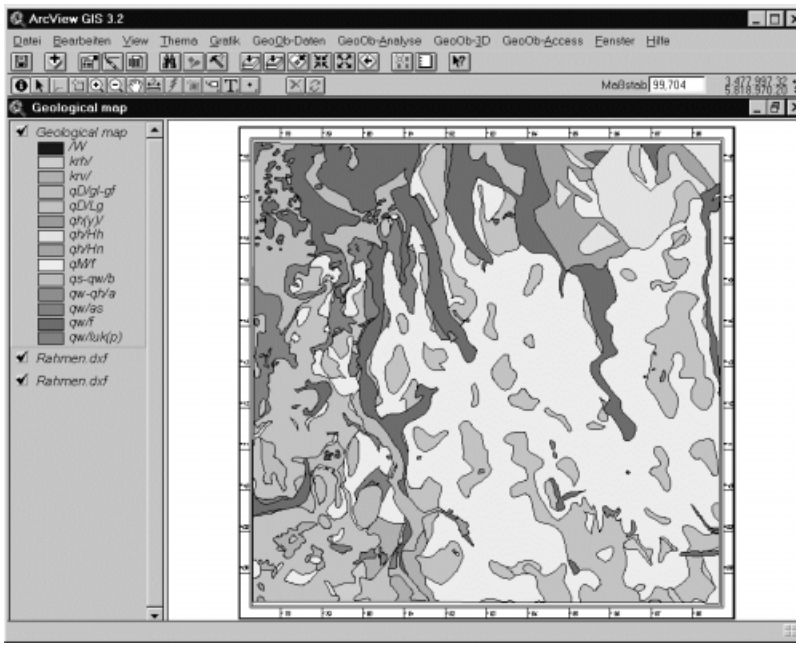

Figure 11.2. Geological map 2 m beneath the land surface in the Diepenau area

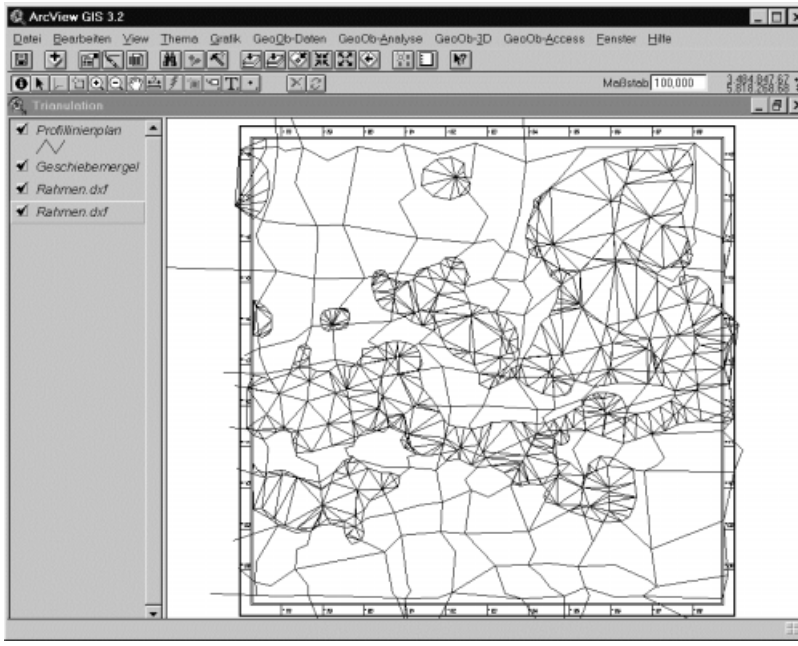

Figure 11.3. Triangulation of all significant points collected from cross sections and lateral boundaries changed interactively (loamy glacial till, Diepenau)

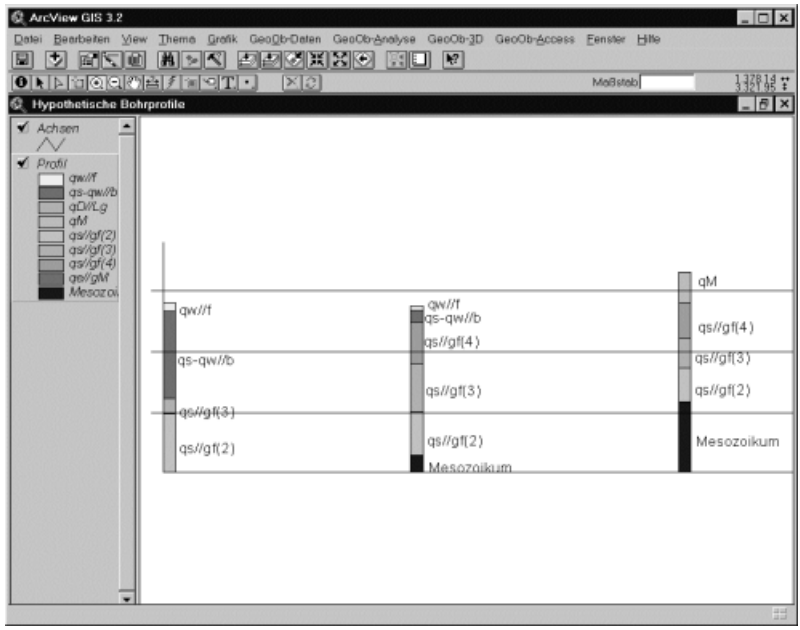

Figure 11.4. Predicted lithology of planned boreholes in the Diepenau area

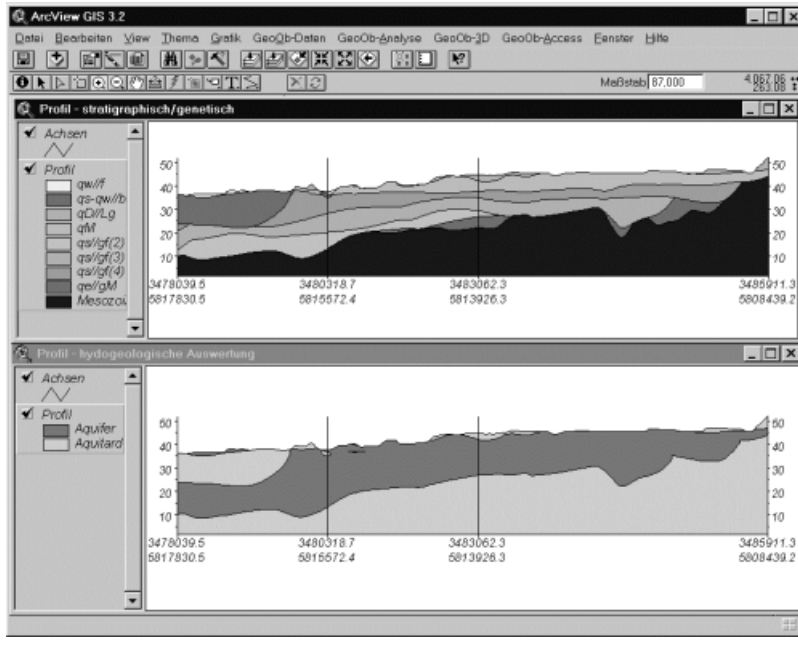

Figure 11.5. Cross-section in the Diepenau area: Upper: Quaternary geology; Lower: hydrogeology

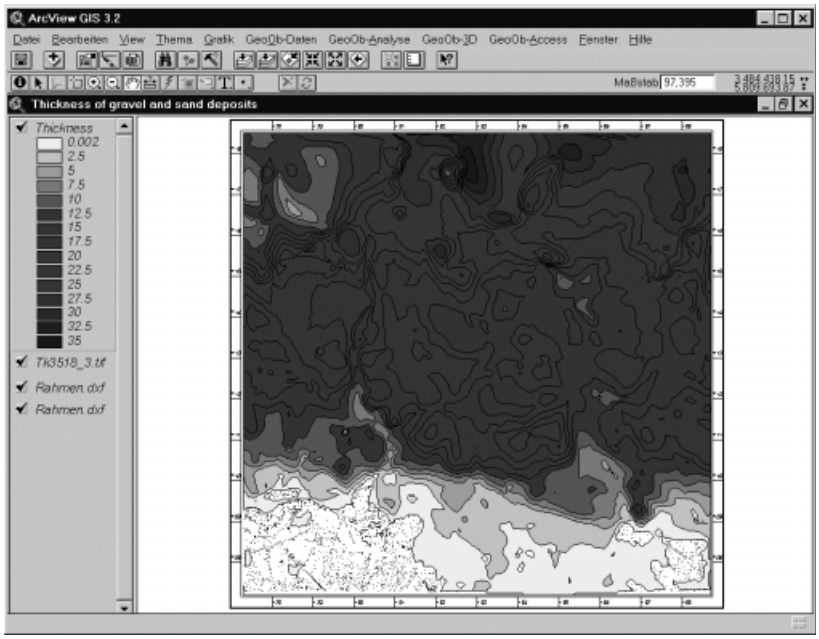

Figure 11.6. Thickness of fluviatile gravel and sand deposits in the Diepenau area

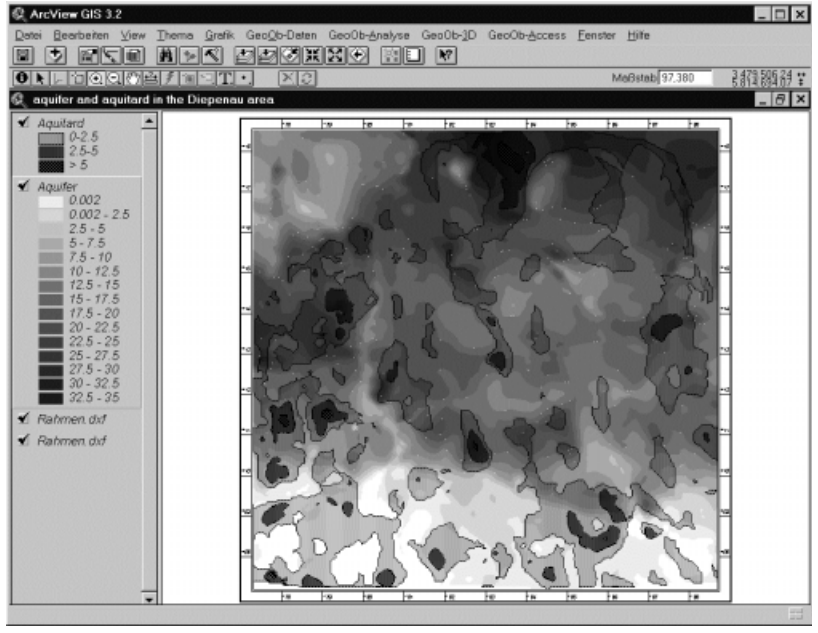

Figure 11.7. Thickness of an aquifer (red) and its cover of loamy glacial till (hatching) in the Diepenau area

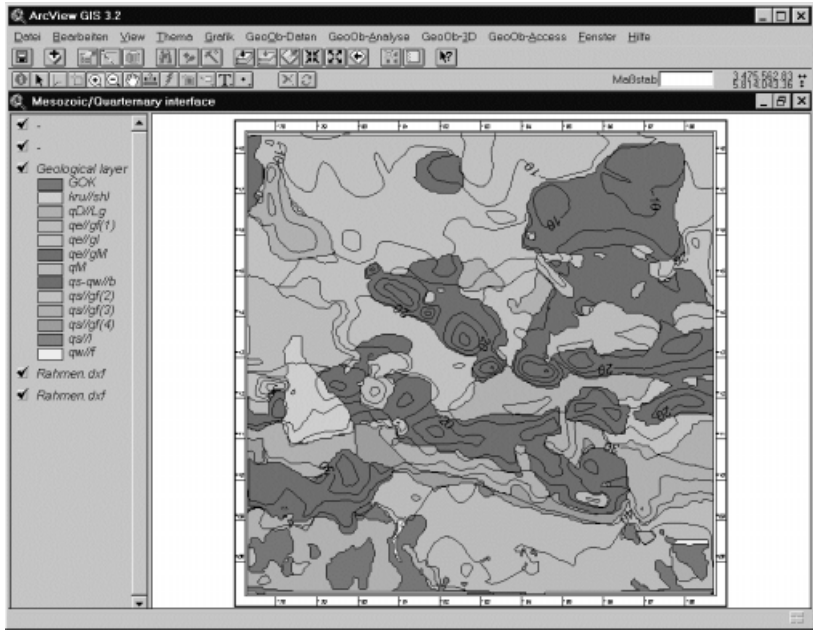

Figure 11.8. The Mesozoic/Quaternary interface (contour lines) and the overlying unconsolidated Quaternary sediments in the Diepenau area

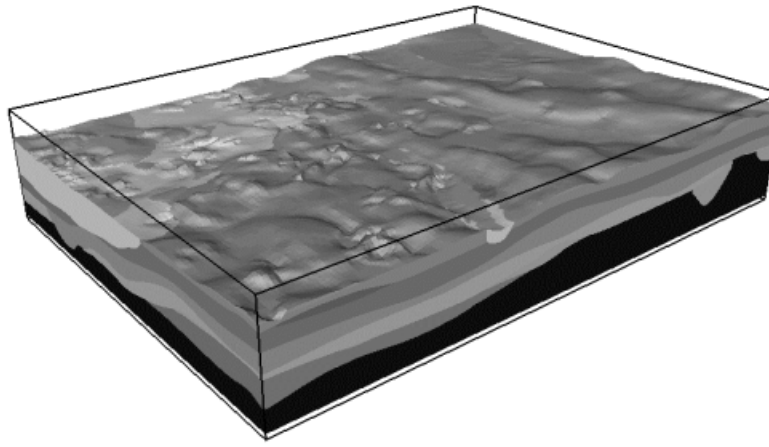

Figure 11.9. Perspective view from the south-west of the Diepenau area [Top shows the geological map of the land surface calculated from the model and projected onto the digital elevation model; walls show the computed cross sections]

12 Slope stability estimation using GIS

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12.1 The Context

Geographical Information Systems (GIS) and Decision Support Systems (DSS) offer help with natural hazard and risk zonation mapping (Burrough and McDonnell, 1998). GIS is able to: **Organize** spatial data, **Visualise** complex spatial relationships of a particular location, make a **Spatial Query** concerning the characteristics of a particular location, **Combine** datasets from different sources, **Analyse** the data (inferring meaning) and make **Predictions** by combining data layers according to purposely embodied rules (Bonham-Carter, 1997).

Hazard mapping related to slope stability is considered to assess the potential contribution by GIS. Landslides are the result of complex processes controlled by many different factors: lithology, geological structure, geomorphological character, land use, groundwater, climate and seismic activity. Climate and seismic activity change periodically, and thus are the two main triggering factors likely to initiate a landslide. Information on lithology, structure and geomorphology can be included in the mapping process, and can form a hazard map since they are not time dependant factors.

Landsliding is the result of rapid change in position of a mass, either natural or man-made, in response to driving forces such as gravity and seismicity. The influence of climate on landslide processes can be considered either as a weathering factor, acting slowly, or rapidly as rainfall, snow or frost. In this paper rainfall is implemented in the model using the pore water pressure ratio (r_u).

12.2 The relevance of GIS to slope stability

One of the main advantages offered by GIS is the possibility of creating hazard occurrence models, permitting evaluation of results and adjusting the input variables. The user can achieve an optimum model by a process of trial and error (Deketh et al., 1997). The large variability of geotechnical properties (cohesion, angle of internal friction), and their host geological units (location) and groundwater condition, is inconsistent with the homogeneity of data required by deterministic models; averaged values are generally sought.

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According to the UNESCO Working Party on the World Landslide Inventory (Popescu, 1996), landslide causal factors may be categorised as:

- Ground conditions
- Geomorphological processes
- Physical processes
- Man-made processes

The hardest problem is to assign the relative weight by which each may be considered to affect the whole system. The GIS model can consider two categories of factors:

- Those derived from a DEM (slope angle, height, elevation, illumination, aspect)
- Those derived from published data, referred to as qualitative information.

12.3 Development of a landslide hazard assessment tool

The study employed a relational database management system implemented within Arc/Info. Methods for calculating slope stability are generally based on the calculation of a Factor of Safety, a function of both geometry of the slope and the geotechnical parameters.

The GIS has been developed as a tool to extract relevant data from Arc/Info for each slope unit, as a facet of the triangulated irregular network built from the elevation data (Figure 12.1). The method is based on a simple approximation proposed by Sah et al. (1994), utilising a circular failure mechanism:

$$F = 2.27 \cdot \frac{c \cdot \cos ec\psi_f}{\gamma \cdot H} + 1.54 \cdot (1 - r_u) \cdot \cot\psi_f \cdot \tan\phi, \qquad (1)$$

Where • : unit weight of soils
c: cohesion
• : internal friction angle
•$_f$: slope angle
H: slope height
r_u: pore water pressure ratio
F: safety factor.

A dynamic tool has been created which enables the user to alter the values of the parameters being used each time a new model is produced. The user can select the values which describe each property according to a desired combination, giving an output as a landslide hazard zonation. Such an approach can incorporate time-dependant changes in value of geotechnical parameters provided a cost effective procedure to monitor them is available.

The methodology has been evaluated against a neural network constructed from 46 case histories of slopes analysed for circular failure by Sakellariou et al. (1996) (Figure 12.2).

The formula has been implemented in a routine in the Arc/Info application using AML (Arc/Info Macro Language) in order to calculate the Factor of Safety for each slope.

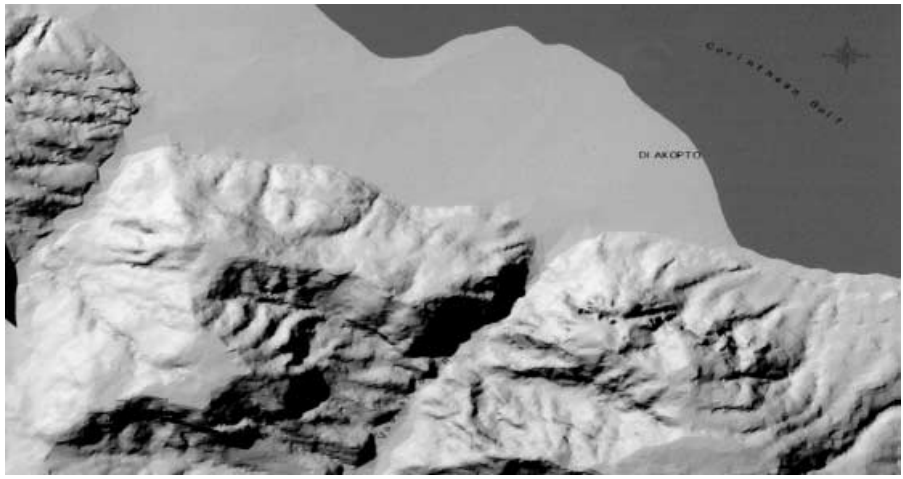

Figure 12.1. Hillshaded map

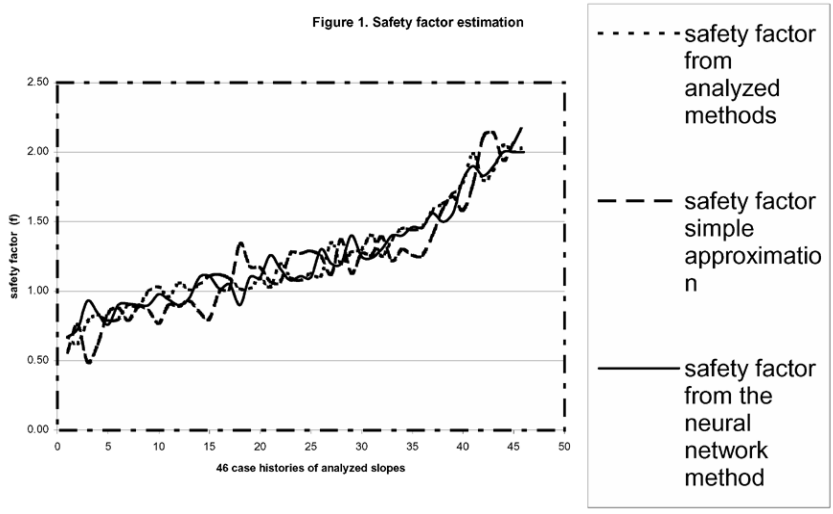

Figure 12.2. Factor of Safety estimation

12.4 Case Study: Diakopto, Greece

The study area covers approximately 48 km^2, situated in the northern part of the Peloponese, 5 km east of the city of Aegio. The valleys of the Vouraikos and Kerinitis rivers cut the area, the former connecting the towns of Diakopto and Kalabryta. The railway connecting the two towns has been affected by rock falls: debris flows and shallow landslides have been recorded along the road nearby.

Weakly cemented marls and sandstones of the Miocene overlie the Mesozoic sequence. The geological setting in which the severest slope instability occurs consists of alternating layers of marls, mudrocks and cherts, overlying thinly bedded limestone. The stratigraphy has frequently been modified by tectonism (Stournaras et al., 1998).

A series of thematic maps has been created taking into consideration lithology, slope angle, elevation, aspect, and rainfall so as to evaluate the hazard. Geometrical factors can be obtained from a digital elevation model (elevation, slope angle, aspect). The geotechnical factors (cohesion, pore water pressure, unit weight, angle of internal friction) are obtained from published sources (Table 12.1).

Table 12.1. Geotechnical parameters.

Geological Formations	Cohesion c Kpa	Unit Weight γ KN/m^3	Internal friction φ degrees
Loose deposits with dominance of fine grains.(Q.f-1)	10–196	15.7–23.5	8°–35°
Loose Deposits with dominance of coarse grains.(Q.c-1)	0–98	19.6–23.5	25°–50°
Loose deposits with dominance of mixed facies.(Q.f,c-1)	29–108	18.1–20.6	10°–40°
Coarse grained formations with cohesion. (Q.c-cm)	196–2943	20.6–27.5	35°–65°
Formations of mixed facies with cohesion. Plio-Pleistocene Deposits (Q.f,c-cm)	304–980	23.0–25.0	38°–46°
Coarse grained sediment (Pl.c)	3041–9810	24.9–25.7	38°–46°
Mainly fine-grained sediments. (Pl.f-c)	2550–5395	23.5–25.0	36°–39°
Preneogenic formations (pNf)	3000–9000	25.0–27.0	40°–60°

Rainfall precipitation in the area is high, and seasonal. Annual rainfall ranges from 800 to 2400 mm; 50 % of the total annual rainfall is concentrated during the winter months (Koukis, 1996). In addition, the surface run-off has a capacity to transport large quantities of material from the catchment. During the dry periods, the ground becomes desiccated and the surface becomes loosened, and prone to erosion. Furthermore the ground desiccates, so that rainwater readily percolates through the cracks, building-up the pore pressure within (Stournaras et al., 1988).

12.5 Landslide hazard zonation

The hazard was defined by Varnes (1984) as the probability of occurrence of a potentially damaging phenomenon within a specified period of time and within a given area. Thus zonation through subdivision of an area into homogeneous do-

mains according to the degree of actual or potential hazard can utilise the landslide model, providing a quantitative estimate of potential landslide occurrence.

The parameters selected for adjustment were: slope angle and slope height (both derived directly from the DEM), and the pore water pressure ratio. The slope height was at first estimated at 50 m for all classes of slope angle, and pore pressure ratio taken as $r_u = 0.00$; there were very few unstable slopes (Figure 12.3). If the value of r_u was raised to 0.50, many slopes would potentially fail (Figure 12.4).

The modelling was repeated for a variety of typical slope angles and heights (20–30° slope 90 m height, 30–40° 100 m, 40–50° 150 m, 50–60° 80 m, 60–70° 60 m). Pore water pressure ratio was varied between 0–0.5.

12.6 Conclusions

In assessing the hazard vulnerability of an area, considerable uncertainty is present. Landslides represent complex multivariable processes. Models are needed to evaluate their consequences, and may be portrayed in the form of hazard maps utilising GIS to create a landslide hazard zonation. By applying this methodology in the Diakopto study area, it was observed that wet slopes of average height have a high risk of instability, consistent with field observations.

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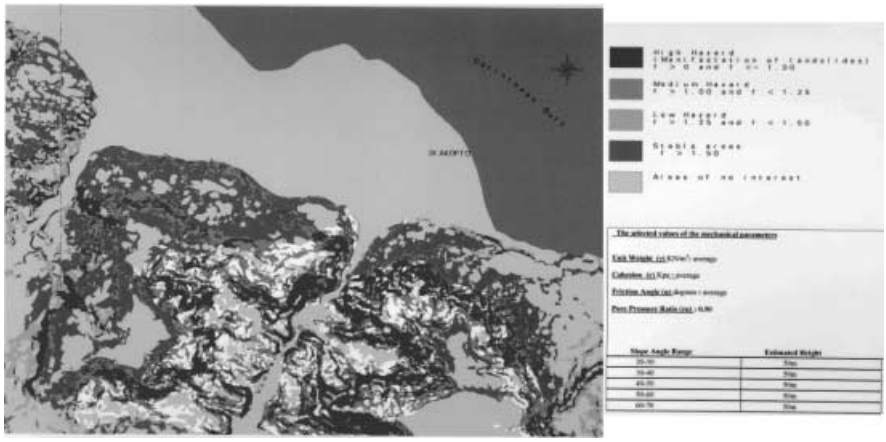

Figure 12.3. Landslide hazard zonation map; stable areas prevail

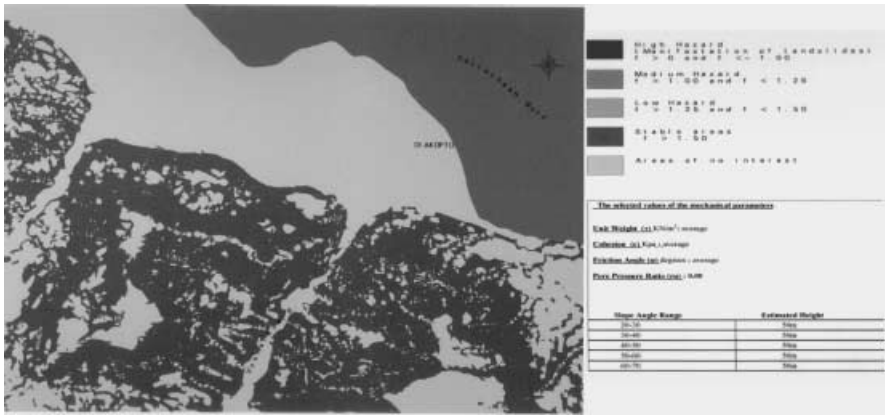

Figure 12.4. Landslide hazard zonation map; medium to high hazard areas prevail

13 Using 2D GIS for the 3D reconstruction of the Corno Zuccone sackung, Val Taleggio (Italy)

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13.1 Context

The development of specialist software for 3D visualisation (e.g. Lynx, g0cad, Earth Vision) permits reconstruction of complex geological bodies. Examples have been published concerning studies based on boreholes and geophysics, but few have concerned mapped structural bodies (de Kemp, 2000).

The systematic use of Geographical Information Systems (GIS) facilitates the management and subsequent analysis and use of geological information contained as cartographic representations in geological maps (Ramsay and Hubert, 1987; Powell, 1992).

13.2 The Corno Zuccone landslide

The Corno Zuccone slide is a deep-seated gravitational slide developed in the sedimentary cover of the Southern Alps (Figures 13.1 and 13.3) along the western part of the Taleggio valley, Bergamo, Italy (Crosta et al., 1999; Zanchi and Stelluti, 2000). This structural sector of the Alpine belt consists of a complex southerly converging stack of thrust sheets comprising a Middle Triassic to Jurassic sedimentary succession. Early to Middle Pleistocene fluvial deposits cover the lower part of the area, indicating strong erosion and dissection of the topography.

The most important gravitational structures consist of E–W and ENE–WSW trending high-angle slip planes, developed within the uppermost part of the Corno Zaccone klippe, suggesting a downward motion of the slipped mass of at least 100–150 m. Geomorphological analysis suggests that the lower (Taleggio) unit, consisting of shales and marly limestones of the Argillite di Riva di Solto Formation is affected by gravitational deformation, involving an area of some 5 km^2. On-going activity of the lower part of the landslide is suggested by building damage (e.g. sliding at Enna bridge in the village of Lavina).

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13.3 Using 2D GIS for 3D modelling in g0cad

The specialist software g0cad has been developed for the creation and management of 3D objects from 2D features such as points, lines and grids. g0cad objects are defined by a finite number of discrete points in 3D space. Their topology is modelled through node connections to which are attributed physical properties (Figure 13.2). Surfaces consist of triangles constructed by interpolation using the Discrete Smooth Interpolator developed by Mallet (1989).

13.4 Reconstructing the Corno Zuccone landslide

The construction of a set of surfaces to define the structure of the local geology is a necessary precursor to reconstructing the geometrical characters of the slide.

Four main sources of information have been used to develop the 3D structural model:

- topographic data represented by contour lines
- geological and tectonic boundaries consisting of 2D linear elements
- structural measurements comprising attitude of bedding, thrusts, strike-slip faults, and gravitational failure surfaces
- geological cross-sections reconstructed from an analysis of the surface geological mapping.

The Arc/Info GIS used for this study essentially worked only with 2D data formats. In order to construct a 3D model, elevation values need to be assigned to each vertex, an operation that can be conducted using g0cad. This requires the construction of a digital elevation model (DEM), obtained by interpolating the 10 m contour lines derived from the 1:10,000 topographic map of the area, employing a 2.5 m pixel side length and a vertical thickness of 0.01 m. The resulting set of points was thinned to a pixel size of 12.5 m before being imported into g0cad. The reconstruction of the topographic surface could then be conducted by interpolation of the point set. Properties such as elevation could then be transferred and linked to the 2D geological boundaries previously imported into g0cad as 'standard' elevation values, subsequently transformed into 3D splines. Further information for constructing the 3D model could then be added from geological cross-sections located within the 3D regular grid as voxels (Figure 13.4).

Structural measurements could then be transformed into down-dip plunge lines of appropriate length (50–100 m) utilised as linear constrains (de Kemp, 1999). Construction of the hidden surfaces such as slide planes and faults, could then be represented as closed surfaces encompassing rigid blocks separated by tectonic elements (Figure 13.5). This operation was realised by the interpolation of linear elements such as vectors derived from mapped data.

In order to reconstruct the fault grid affecting the Corno Zuccone klippe, cross-cutting relationships among the different tectonic structures had first to be established, starting with a perspective view (Figure 13.6a). Based on field relationships, gravitational surfaces are likely to be the most recent. A relative chronology can then be used to reconstruct the fault sets, starting with the youngest. Gravitational structures would be expected to be listric, progressively flattening (Figure 13.6b). This is supported by the superficial trace of the structures and by the mechanical properties of the displaced rock bodies. Strike-slip faults would be expected to have a vertical orientation and thus be distinguished in their outcrop pattern from low-angle thrust or high angle normal faults (Figure 13.6c).

The application of this approach to the Corno Zuccone landslide, using both geometrical and numerical modelling, suggest the possibility of a sackung-type deformation for the Corno Zuccone deep-seated gravitational slide, partially due to sagging of the klippe (Zischinsky, 1966, 1969; Radbruch-Hall, 1978; McCalpin and Irvine, 1995).

In order to check the mechanism of formation of the sackung, a basal surface has been reconstructed using surface elements such as the trace of the main scarp and part of the drainage pattern. The reconstructed planes are likely to be underlain by a basal 'detachment' surface, suggested by geomorphological indications (Figure 13.6d). Such 'construction and disruption' of the sackung can be undertaken with g0cad (Figure 13.7).

In order to check in 3D the consistency of the 2D sections used to reconstruct the sackung, a similar operation was followed to restore them to their pre-sliding position (Figure 13.8).

13.5 Discussion

The procedure has demonstrated that 3D modelling can examine and check for geometrical consistency, even when only surface data is available. The use of 3D visualisation software strongly enhances the understanding of geological structure and the recognition of solutions that are not plausible. 3D surfaces have been realised using g0cad through the reconstruction of topographic surfaces interpolated from point sets extracted from a DEM and subsequent attribution of elevation properties to 2D lines (Mallet, 1990). Thus a 3D geological model of the Corno Zuccone massif has been constructed, taking into account surface geology and subsurface interpretations obtained from cross-sections.

Based on the geometrical reconstruction, it has been possible to compute isopachs of the Corno Zuccone slide and the potential for parameterisation as a basis for geotechnically modelling the slope stability.

Crosta *et al.* (1999) developed numerical models with UDEC, a distinct element code (ITASCA, 2000). Their first model was based on a triangular section of the Corno Zuccone klippe, and the second considered a trapezoidal section. The latest work suggests that only the second situation is plausible, thus constraining the possible failure mechanisms.

Furthermore, the displacement of the klippe suggests that deformation cannot be accommodated by plastic deformation of the lower unit alone, and that a basal shear plane must also be active. The strong increment of y-displacement below the klippe suggests the occurrence of a shear plane, and thus is almost coincident with the main shear plane obtained using geometrical reconstruction techniques.

The triggering factor for the sackung may be related to a rapid deepening of the valley bottom suggested by the recent excavation of the Enna gorge in the eastern part of the Taleggio Valley.

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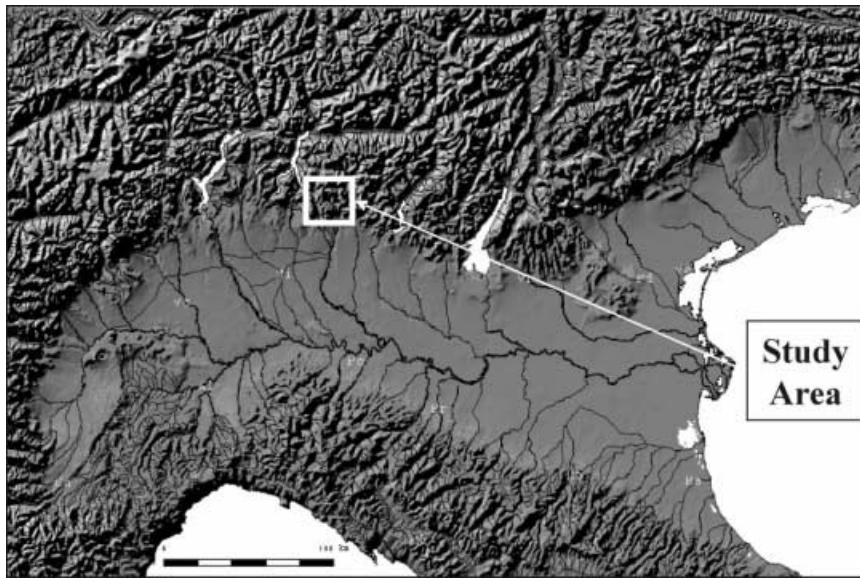

Figure 13.1. Shaded relief map of Northern Italy showing location of study area

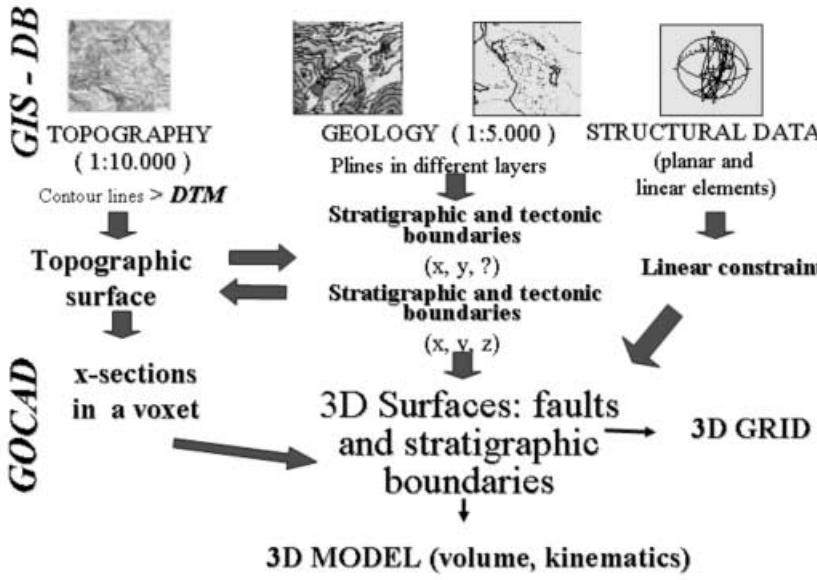

Figure 13.2. Flow diagram relating GIS and g0cad through 3D modelling

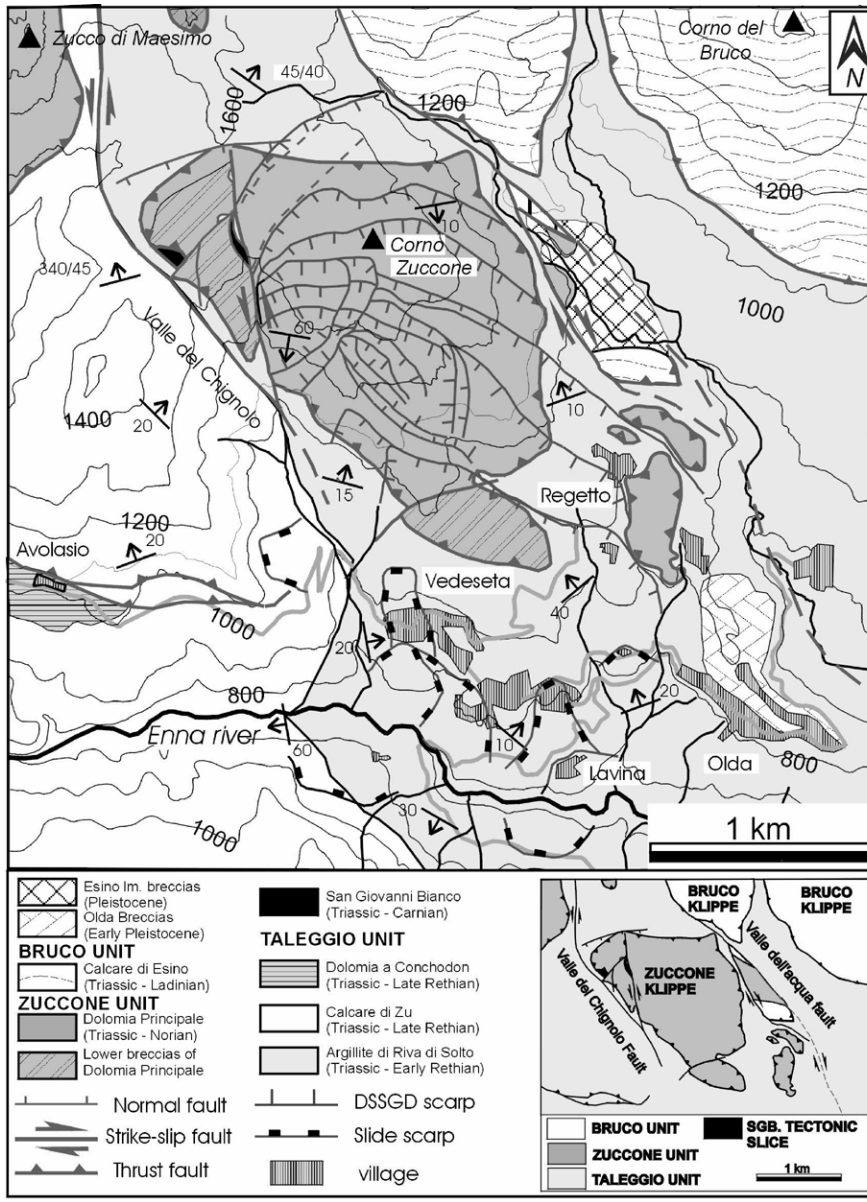

Figure 13.3. Geological map of the western Taleggio. *Inset*: tectonic structure

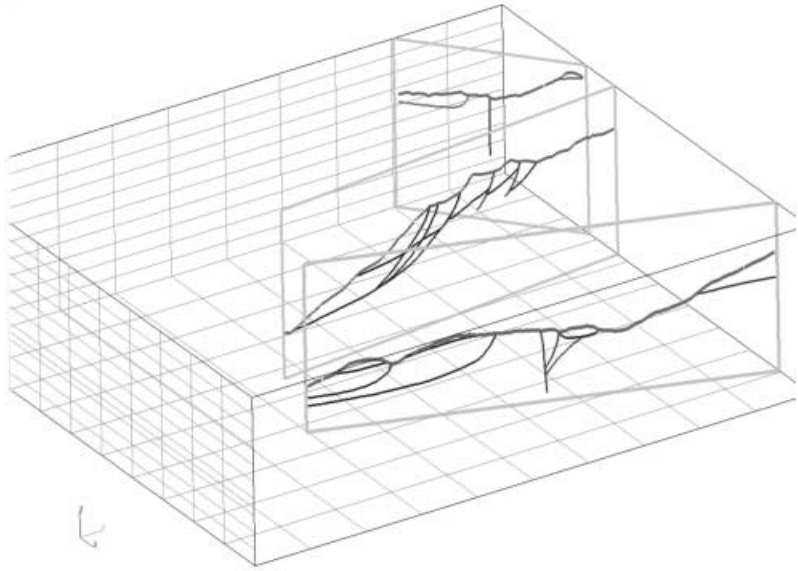

Figure 13.4. 3D modelling with g0cad showing construction of geological cross-sections in the context of a voxel structure

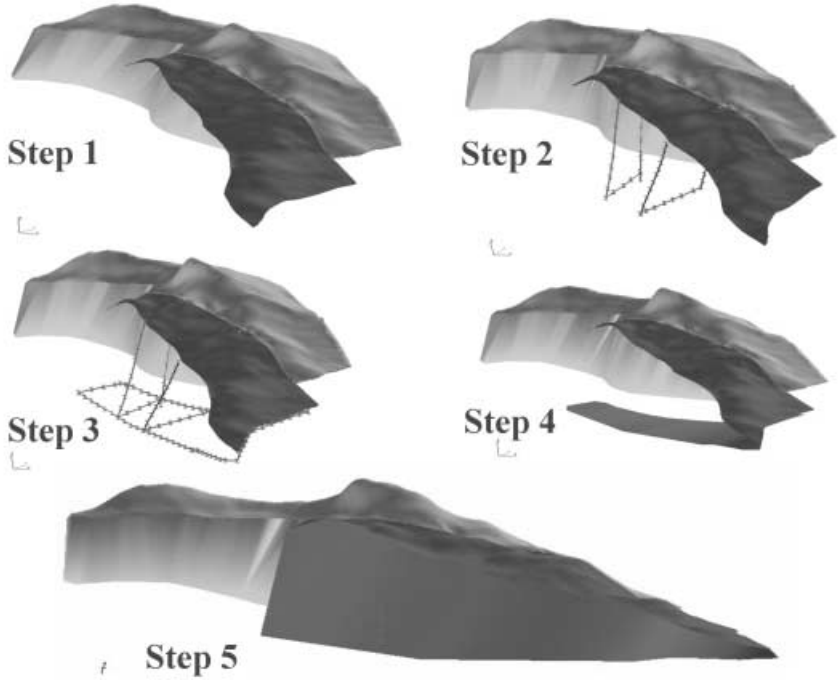

Figure 13.5. 3D modelling with g0cad showing construction of complex geological bodies (closed surfaces) through the generation of surfaces obtained from linear elements

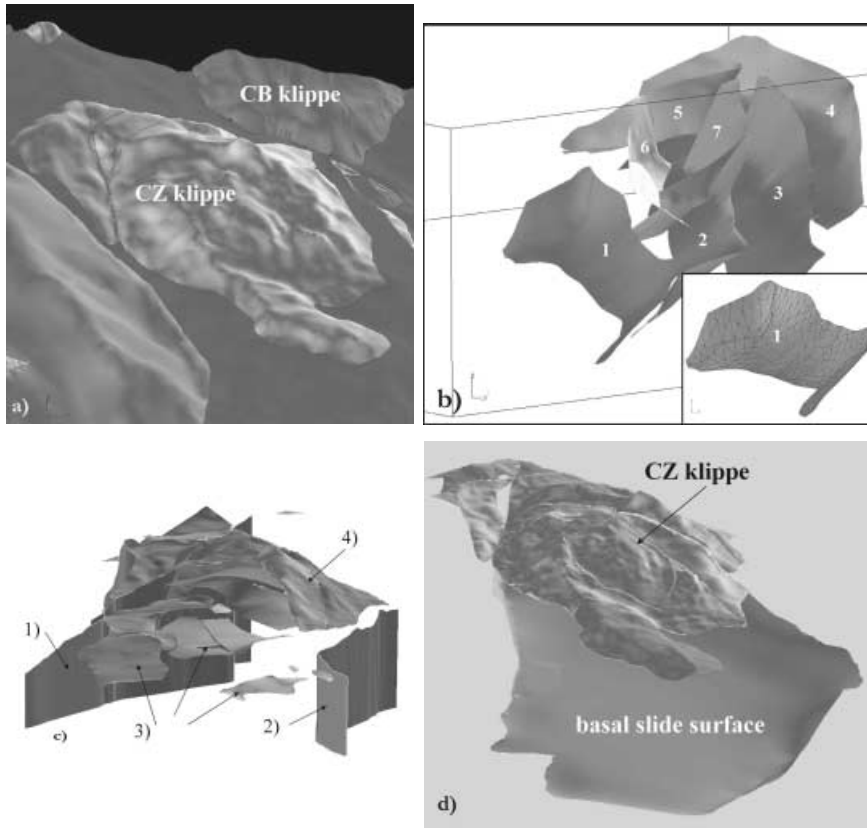

Figure 13.6. 3D models for Corno Zuccone

(a) Perspective view of the surface geology of the area showing the Zuccone klippe

(b) The main structural elements of the area: 1) Valle del Chignolo left lateral strike-slip fault, 2) Valle dell'Acqua right lateral strike-slip fault, 3) basal thrust surfaces of the CZ, 4) topographic surface of part of the top of the CZ klippe

(c) Some of the main gravitational sliding surfaces displacing blocks of the Corno Zuccone klippe. Note the fine triangular network of surface 1 created by g0cad

(d) The Corno Zuccone klippe and the basal surface of the deep slide.

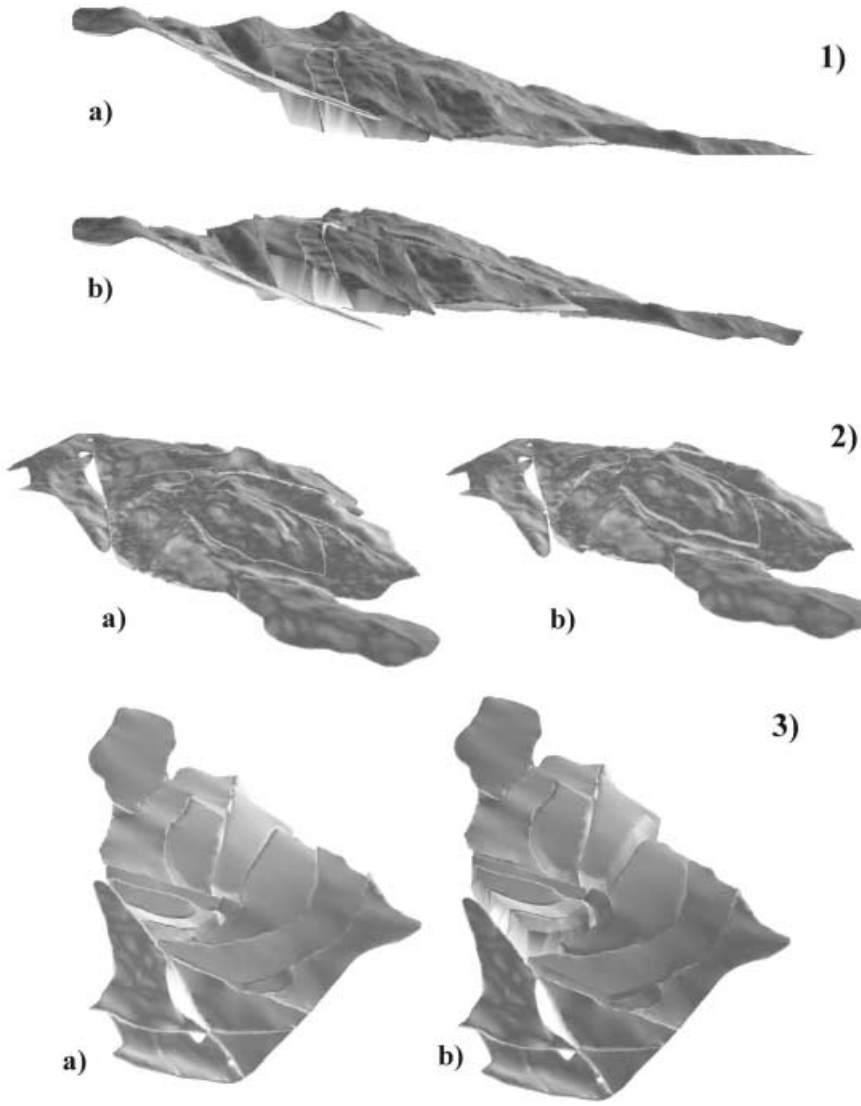

Figure 13.7. 3D retrodeformation of the klippe of Corno Zuccone: 1) lateral view; 2) frontal view; 3) bottom view of the basal thrust surface. a) pre-sliding situation; b) post-sliding situation.

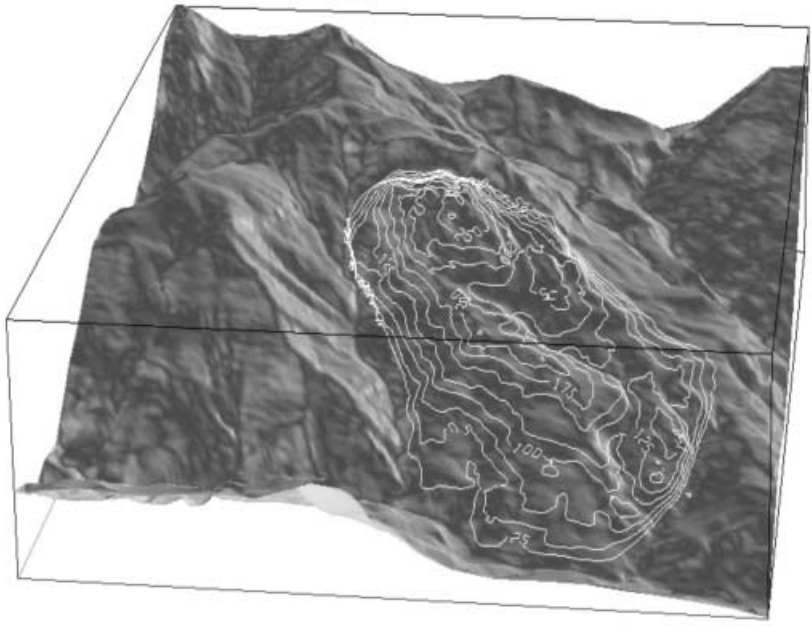

Figure 13.8. Reconstruction of the sackung. Contour lines every 25 m

14 Sedimentation modelling: data analysis in Rotterdam Harbour

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14.1 Introduction

Sediment accumulation within ports and harbours requires dredging to maintain sufficient draft for shipping. Design of the dredging operation requires knowledge of the amount and composition (sand-sludge ratio). Sedimentation results from several geological processes. Harbours naturally form effective sediment traps. Some areas of Rotterdam harbour derive relatively clean sand from the North Sea through tidal action, whereas other areas accumulate contaminated clay transported by the River Rhine.

Parameters that quantify sedimentation include: the rate of discharge from the Rhine, the physical and chemical composition of the sediment, and the flux. In order to manage the port, these various processes have to be considered, the goal being to predict the rate and location of sedimentation within the harbour basins.

14.2 Sedimentary environments

The port of Rotterdam is located at the confluence of two major river systems as they enter the North Sea: the Rhine and the Meuse. The sediment flux from the Rhine is about five times that from the Meuse, the former discharging 2500 m^3/s compared to the Meuse discharging 200 m^3/s. These rivers mainly carry fine-grained material in suspended state, or by bottom transport.

The North Sea is also a major source of sediment, consisting mainly of sand and silt. These coarser sediments mainly originate from storm erosion of coastal cliffs in northern France, carried towards the Dutch coast by the northerly longshore drift. Before reaching the Maasmond area (which acts as a major sediment trap), the sediment is likely to have been deposited and eroded several times. The Western Scheldt, Eastern Scheldt and the Haringvliet outlet areas have extensive sandbar systems which act as buffer zones trapping and eroding the sediments as they move northwards (Figure 14.1).

Currents within Rotterdam Harbour are influenced by river and tidal flow. The difference between high and low tide is approximately 2 metres. The turbidity

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maximum is located a little west of Botlekhaven (Figure 14.2), forming a major transition from sedimentation predominantly originating from the North Sea from that which is mainly fluvial.

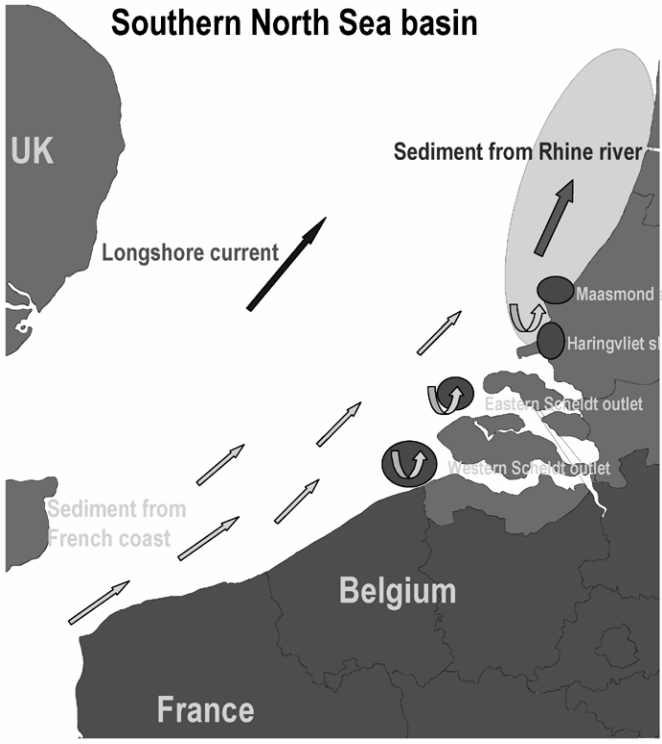


Figure 14.1. Sediment transport north towards the Dutch coast

14.3 Harbour study areas

Three areas within the port of Rotterdam were selected in consultation with the Rotterdam Municipal Port Management and the Ministry of Transport, Public Works and Water Management. Sedimentation is believed to be influenced predominantly by tidal flow (i.e. the North Sea), by both tidal flow and river flow, and by predominantly river flow. The three study area locations shown in Figure 14.2 are:

- **Maasmond** An area in the western part of the harbour, mainly influenced by the sea
- **Botlekhaven** An area in the central part of the harbour which is influenced by both the river and the sea.

- **Waalhaven** An area in the eastern part of the harbour, mainly under the influence of the river

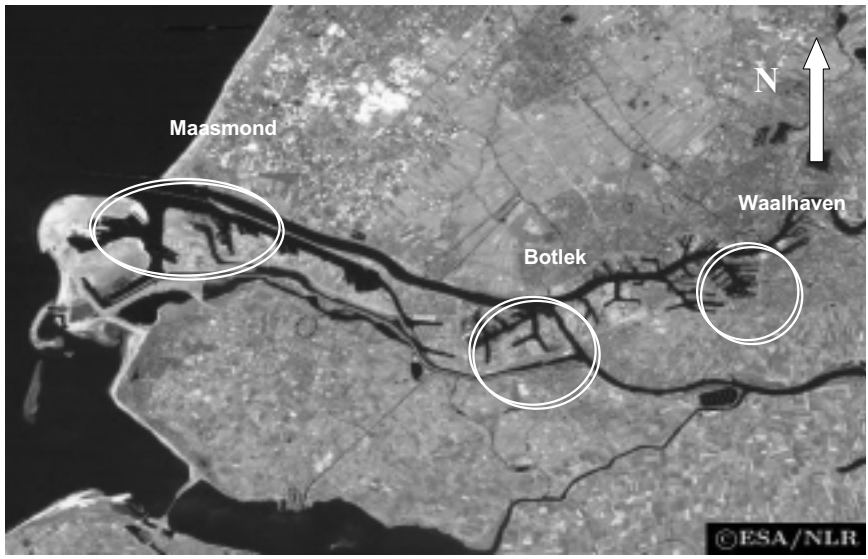


Figure 14.2. Rotterdam harbour area (source ESA/NLR)

The Maasmond area has the largest data set of the three study sites and is the main focus of the investigation being reported. Here the shipping channels are maintained at a nautical depth of 24 metres, more than twice as deep as the surrounding bottom profile. Dredging in this area is continuously in progress but promotes accelerated sedimentation. Yearly sediment fluxes of 2.0 Mt of (dry solid) sand and 2.8 Mt of silt occur (Dreumel et al., 1995).

14.4 Data mining

Extracting knowledge concerning the study areas from pre-existing information is an essential precursor to identifying the processes that could influence harbour sedimentation. Attention has been focussed on data handling systems that could facilitate data exploration ('mining') and form the basis of predicting spatial and temporal variations.

Increasingly, use is being made of pre-existing data for building the process model. Direct ('raw') data consists of the original measurements without any processing. Indirect data refers to the measurements that have been collected and subsequently processed. For the Rotterdam Temporal and Spatial Sedimentation Predictions study (TSSP), the major data set consisted of indirect values, primarily from single- and multi-beam measurements. The data have been stacked, averaged, adjusted for depth and position and then gridded. The data that has been

gathered covers a 10-year period from 1991–2000 at intervals of a few weeks to several months (Table 14.1).

Table 14.1. Measured variables.

Type	Variable	Spatial and/or temporal data
Indirect	Bathymetry	Spatial and temporal
Indirect	Dredging volumes and tracks	Spatial and temporal
Indirect	Dredging densities	Spatial and temporal
Indirect	TDS	Spatial and temporal
Indirect	Difference 210 - 33 kHz (fluid mud indicator)	Spatial and temporal
Direct	In situ density probes	Dominantly temporal
Indirect	Sediment composition	Dominantly temporal
Indirect	Flow measurements	Dominantly temporal
Direct	Chlorid content	Dominantly temporal
Direct	Watertemperature	Dominantly temporal
Indirect	Discharge of rivers	Dominantly temporal
Direct	Waterlevel	Dominantly temporal
Direct	Astronomical tide	Dominantly temporal
Indirect	Surge	Dominantly temporal
Direct	Suspended sediment concentration	Dominantly temporal
Direct	Wind speed and direction	Dominantly temporal
Direct	Wave energy (height, period, direction)	Dominantly temporal
Direct	Chlorophyll content	Dominantly temporal
Direct	Ship movements	Dominantly temporal
Direct	Historical events	Dominantly temporal
Indirect	Distance to shipping lane	Dominantly spatial
Indirect	Distance to shore	Dominantly spatial
Indirect	Waterdepth	Dominantly spatial

14.5 Data-driven modelling

The general approach taken for prediction has been to construct a data-driven model as depicted in Figure 14.3. The GIS is used for visualising the data distribution and performs spatial analysis. The volume has been calculated by taking the difference between two time intervals projected onto a regular grid. It is ultimately upon volume estimates that the artificial neural network will be trained. Figure 14.4 shows a difference map of one time interval for the 'real' deposited volume.

An Artificial Neural Network (ANN) has then been trained to assist identification of input parameters significantly influencing the sedimentation. The network is trained using a training set, tested using a test set and validated using a validation set, each set being unique.

The data were compiled from five different sources, each organisation having its own way of collating and storing the data, as well as geo-spatially referencing it. However, the data needs to be matched and integrated, so achieving a comparable resolution in space and time.

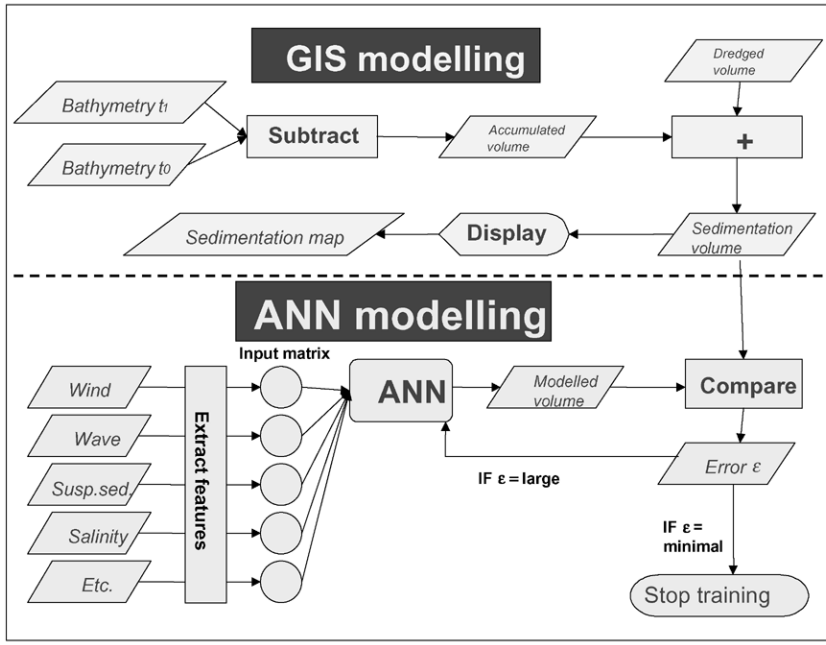


Figure 14.3. Flow diagram for the modelling approach

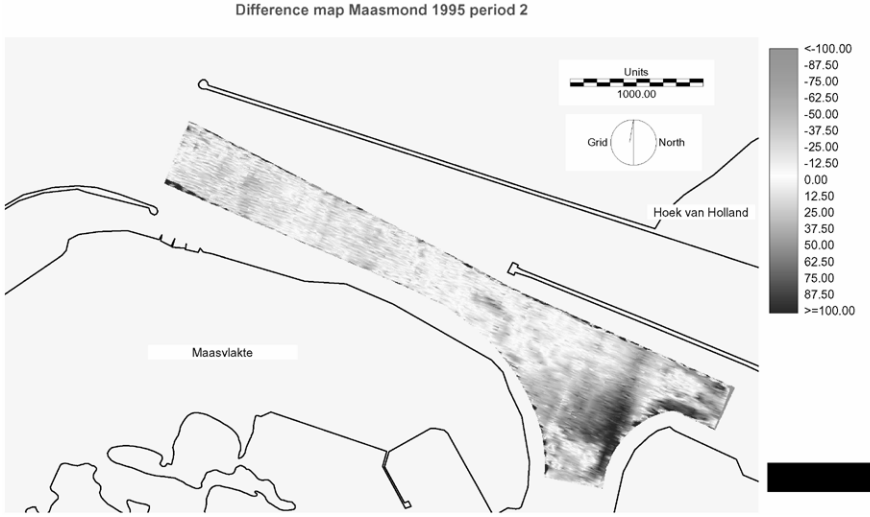


Figure 14.4. Map showing the change in water depth for a specific time interval in the Maasmond area, the tone indicating the degree of erosion or accumulation

The sedimentation can be forecast once every 2 weeks, limited by the sampling frequency of the bathymetric surveys. The optimum sampling frequency is proba-

bly more often than two weeks, but not economically justifiable for the purposes of the dredging programme. More important is that the sampled parameter be based on a sufficient measurement population.

The data contains inconsistencies resulting from differences over the decade of acquisition, including data loss and changes in equipment. In the early 1990's little data was stored digitally even though it had been acquired in digital format. Increased computer capacity towards the end of the decade now permits better data handling and storage, better documentation (i.e. metadata).

The diversity of project objectives has resulted in many different measurement locations. For instance, wind and wave measurements have been taken at one location near the study area, whereas river discharge and suspended sediment concentration were measured at another location, yet both sets of measurement provide data relevant to the sedimentation processes.

The quality of the data is also variable. Precision of the measurement devices varies, and sometimes pre-processing has had to be performed.

14.6 Parameter evaluation

Sediment transport and depositional processes are influenced by many parameters. Their identification is the first goal for a consideration of harbour siltation. The linking of ANN to the GIS has enabled the following parameters to be recognised as having influence on the sedimentation process. Those directly influencing the process (independent parameters) have been listed separately from those indirectly influencing the process (semi-dependent parameters).

Independent parameters:

- Geography and bathymetry
- Tidal currents
- River discharge
- Wind-speed and wind-direction

Semi-dependent parameters:

- Wave energy
- Surge
- Chloride content
- Suspended sediment concentration
- Chlorophyll content
- Water-temperature
- Sediment composition

Other parameters considered:

- Historical events (deepening of channels, construction of artificial land)
- Ship movements
- Distance to shore
- Distance to shipping lane

For each of these parameters, data had been collected over the decade 1991–2000. The next step was to identify the most important parameters influencing the sedimentation process in the research area.

The most influential parameters have been identified in three ways:

1. **Correlation analysis**: calculating the correlation coefficient between sediment volumes and each of the other parameters, especially the time lag between different events (Table 14.2).
2. **Principal component analysis**: A factor extraction method for linear combinations of variables where the first component has the maximum variance.
3. **Parameter ranking opinion poll (PROP)**: Several experts familiar with sedimentation processes examine the list of parameters and provide their 'opinion' as to which parameters should be related to each other, to what degree and which parameter would dominate. The degree of relationship and dominance from the group can be quantified numerically as a 'relation-matrix' (Table 14.3 gives the results of one such poll).

At first glance the correlation coefficients shown in Table 14.2 appear rather low. However, many of the parameters are correlated. Furthermore, the correlation coefficient is a measure only for linear dependency.

Table 14.2. Correlation coefficients for parameters likely to influence sedimentation. On the right, weights of the parameters having the first two principal components are indicated.

Parameter	Correlation type	Correlation coefficient				PCA Component	
		vs Average		vs Variance		1	2
		sed e*	sed f*	sed e	sed f	35%	20%
Windspeed at Hoek of Holland	Cross Correlation	0.29	0.17	0.30	0.25		
	Time lag (weeks)	-12	-8	-12	-12		
Windspeed at Europlatform	Cross Correlation	0.32	0.24	0.31	0.29	0.603	0.586
	Time lag (weeks)	-12	-6	-11	-7		
Discharge Haringvliet	Cross Correlation	0.36	0.43	0.22	0.30	0.862	-0.294
	Time lag (weeks)	-3	4	2	6		
Discharge Maassluis	Cross Correlation	0.39	0.50	0.38	0.33	0.66	-0.513
	Time lag (weeks)	0	6	-12	-10		
Discharge Lobith	Cross Correlation	0.40	0.49	0.30	0.37	0.872	-0.342
	Time lag (weeks)	2	5	6	6		
Surge at Hoek van Holland	Cross Correlation	0.24	0.22	0.46	0.36	0.546	0.547
	Time lag (weeks)	19	10	-11	-9		
Significant waveheight at Europlatform	Cross Correlation	0.39	0.35	0.34	0.27	0.664	0.605
	Time lag (weeks)	-12	-4	-13	-11		
Suspended sediment Lobith	Cross Correlation	0.29	0.29	0.23	0.25	0.69	-0.236
	Time lag (weeks)	5	6	5	5		
Suspended sediment Maassluis	Cross Correlation	0.36	0.40			0.422	-0.296
	Time lag (weeks)	0	-3				
Watertemperature at Maassluis	Cross Correlation	-0.52	-0.43			-0.366	-0.03
	Time lag (weeks)	-2	0				
Chlorid content at Maassluis	Cross Correlation	-0.31	-0.37			-0.29	0.51
	Time lag (weeks)	4	12				
Chlorophyll concentration at Maassluis	Cross Correlation	-0.55	-0.36			-0.09	-0.297
	Time lag (weeks)	-12	-15				
* Control volume under research (either E or F) in the Maasmond area							

A total of 5 principal components were extracted from twelve parameters, the first two together account for 55% of the variance in the data set. Some of the parame-

ters are correlated and ideally one should only consider parameters that are independent of each other. Since the analysis is used just for indicative purposes, the values should be treated with some caution.

On the basis of the correlation analysis, PCA and PROP, preliminary model parameters could be selected, as shown below. These can then be linked to the sedimentation volume as an output parameter.

- Weekly variance of windspeed
- Wind direction
- Weekly averaged river discharge
- Weekly variance of surge
- Weekly averaged wave energy
- Wave direction
- Weekly averaged / interpolated suspended sediment concentration
- Weekly averaged / interpolated chloride content
- Weekly averaged / interpolated chlorophyll concentration

The historical data has been interpreted as shown in Figure 14.8. The selected data format was ASCII in order to permit exchange of text between databases. The files were screened for obvious erroneous measurements and missing values. Metadata proved very important for permitting an overview and quick referencing of information, including the source, type of data, parameter, time interval, missing value indicator, processing, remarks, name of processor and the date.

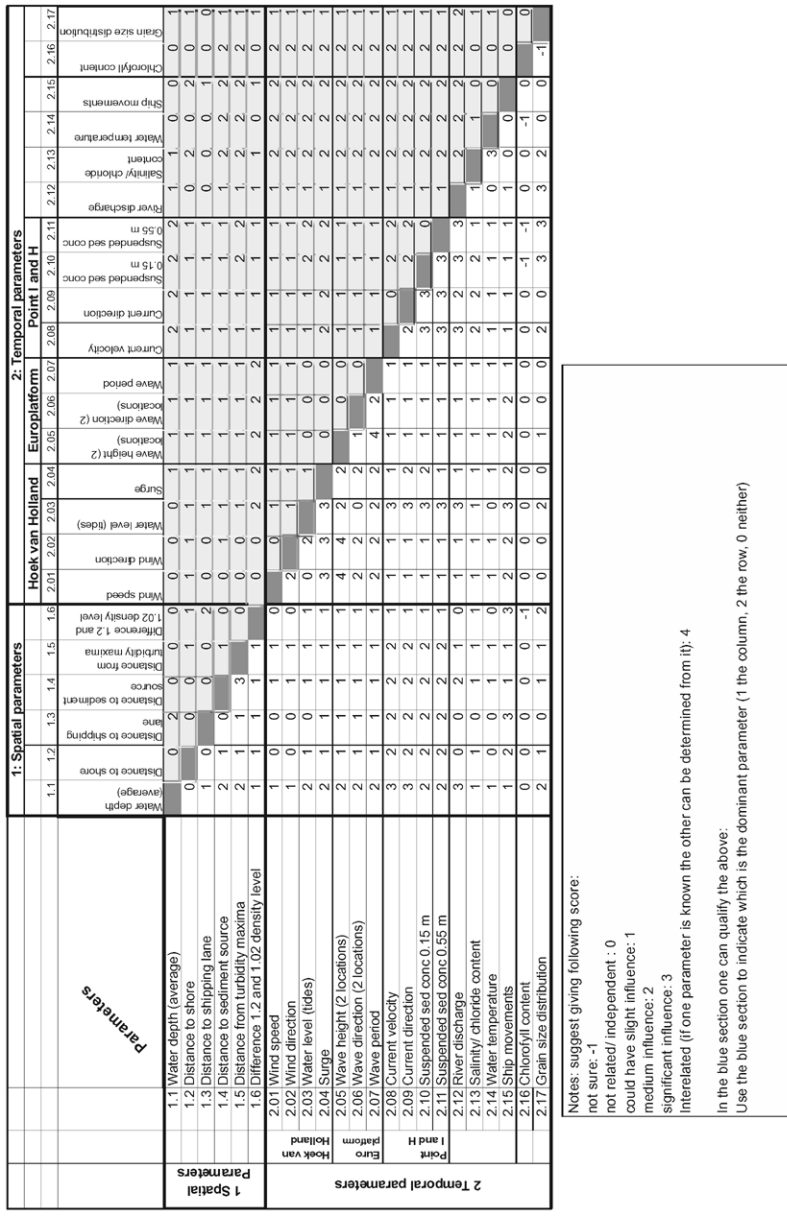
14.7 Conclusions

The primary objective was to establish a protocol that could predict volumes expected for dredging maintenance. This was to be based on trends recorded during the previous ten years together with expert knowledge.

The end users of the model are the Rotterdam Harbour Authority and the Ministry of Transport, Public Works and Water Management. The main purpose is to predict sediment volume accumulation for planning dredging activities.

Procedures have been developed to examine existing 'second-hand' data to determine those parameters most influential on the sedimentation process, assisted by linking ANN to the GIS.

Table 14.3. Example of a PROP (Parameter Ranking Opinion Poll). The lower half of matrix stores the expert's anticipated degree of correlation. The upper half of the matrix indicates the dominance of one parameter over the other.



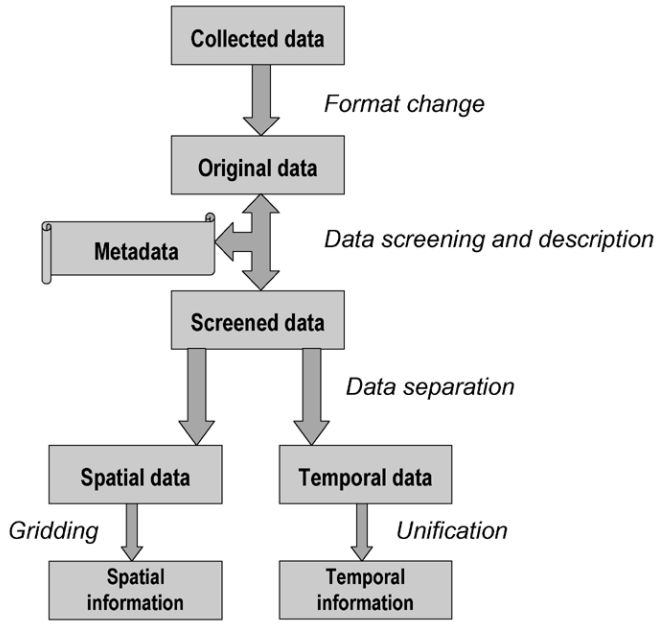


Figure 14.8. Process of data handling

Acknowledgements

The Port of Rotterdam data set and the analyses of this data has been carried within the Delft Cluster project called 'A sedimentation model for the Port of Rotterdam'. Participants in the Rotterdam modelling project are: the Port of Rotterdam, Rijkswaterstaat directorates North Sea and South Holland (Department of Public Works and Water Management), Nottingham Trent University, and the Delft Cluster institutes: TU Delft, IHE, Delft Hydraulics and GeoDelft.

Reference

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15 Fluid flow in fractured formations

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15.1 Introduction

Fractures are widespread in the ground. Their morphology affects substantially the transport of non-aqueous phase liquid (NAPL) pollutants within the groundwater regime (Sahimi, 1995). Past work has focused on the development of numerical simulators that solve the macroscopic transport equations in fractured reservoirs (Choi et al., 1997; Gerke and van Genuchten, 1993). Little progress has yet been made on elucidating the interactive effects of single fracture morphology and fluid rheology on the flow through single fractures (Federico, 1998; Fourar et al., 1993; Rossen and Kumar, 1992; Zimmerman and Bodvarsson, 1996).

The most widely used flow model for a rock fracture is the parallel plate model. This is the only fracture model for which an exact calculation of the hydraulic conductivity is possible and yields the well-known 'cubic-law' (Adler and Thovert, 1999). However, fractures have rough walls and variable apertures with extensive contact between the opposing faces (Zimmerman and Bodvarsson, 1996). Fluid flowing in a variable aperture fracture will tend to follow paths of least hydraulic resistance and they will depart from the rectilinear streamlines of the parallel plate model (Silliman, 1989).

The techniques of 3D fracture reconstruction from correlation functions of 2D images can be used to characterise single fractures (Adler and Thovert, 1999). However, the straightforward simulation of fluid flow in such structures requires a substantial amount of computational effort (Sahimi, 1995). The representation of fractures with pore network models, though less accurate, allows the mathematical treatment and fast numerical simulation of fluid flow in single fractures (Klint and Tsakiroglou, 2000; Rossen and Kumar, 1992). Recent optical studies of 2D SEM images of fractures have revealed that a single fracture resembles with a disordered two-dimensional network of elliptical channels (pores).

The majority of organic liquid pollutants (NAPLs) that may contaminate the ground (e.g. mixtures of hydrocarbons, crude oil, asphalt, lubricating engine oils, polymer leachates) exhibit varying degrees of deviation from the linear flow behaviour of Newtonian fluids (Rossen and Kumar, 1992; Wardaugh et al., 1988). Additional non-linearities are thus introduced to the micro-flow mechanisms. The fluid flow through pores becomes complex even for simple geometries (Ikoku and

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Ramey, 1979; Kadet, 2000), but the conventional Darcy's law would no longer be valid (Sahimi, 1993; Shah and Yortsos, 1995).

There is a need for the production of new phenomenological equations relating the superficial flow velocity with the pressure gradient along the porous medium (Sahimi, 1996). With the aid of critical path analysis of percolation theory and volume averaging, several non-Darcian equations have been developed about the single-phase flow of power law fluids in homogeneous porous media (Sahimi, 1993; Shah and Yortsos, 1995). Unfortunately, the shear stress-shear rate relationships of most organic fluids rarely fit with simple power law models (Al-Zahrani and Al-Fariss, 1998; Wardaugh et al., 1988).

Macroscopic momentum balances of the flow of generalised non-Newtonian fluids through porous media have been formulated by using volume averaging techniques (Liu and Masliyah, 1999), and corresponding phenomenological models have been derived for the laminar flow of Herschel-Bulkley and Meter fluids in packed beds (Liu and Masliyah, 1998). Although the role of the macromolecules on the flow of polymer solutions in porous media has extensively been studied (Sorbie, 1990; Sorbie and Huang, 1991), few attempts have ever been made to analyse fluid memory visco-elastic effects (Bird et al., 1977; Macosko, 1994) on polymer flow through pores (Souvaliotis and Beris, 1992).

The aim of the present work has been the development of a non-Darcian phenomenological model for the 1-phase flow of inelastic and time-independent non-Newtonian fluid through a single fracture. This has been tackled using artificial glass-etched single fractures by combining flow simulations in pore networks with effective medium approximation (EMA).

15.2 Laboratory experiments

Ozokerite (natural mineral wax) dispersions in paraffin oil were selected as synthetic NAPLs because of their shear-thinning behaviour and stability.

The shear stress-shear rate relationships were measured by using a Dynamic Stress Rheometer (Rheometric Scientific, SR-200). All measurements were performed on a cone and plate geometry by using the steady stress sweep method. The rheological properties of synthetic NAPLs were very sensitive to ozokerite concentration (Figure 15.1) and hence they were able to be controlled easily by varying this parameter. The classical power law and generalised Herschel-Bulkley models (Bird et al., 1977; Liu and Masliyah, 1998) were found inadequate for the description of the rheology of synthetic NAPLs over the entire range of ozokerite concentrations. Instead, the experimental data were found to fit satisfactorily to the Meter fluid model (Kozicki and Tiu, 1973; Meter and Bird, 1964) described by

$$\mu = \mu_\infty + \frac{\mu_0 - \mu_\infty}{1 + \left(\tau/\tau_c\right)^{n-1}} \tag{1}$$

and the new mixed Meter-and-Power Law fluid model given by:

$$\mu = K^{1/m}\tau^{1-1/m} + \frac{\mu_0 - K^{1/m}\tau^{1-1/m}}{1+(\tau/\tau_c)^{n-1}} \quad (2)$$

where μ_∞ , μ_0 are asymptotic Newtonian viscosities at low and high shear stresses, and τ_c is a characteristic shear stress value.

The parameter values of both models were estimated through non-linear least square fitting (Bard, 1974) to the rheological data (Figure 15.1), and the results are given in Table 1. The mixed model reproduces the NAPL rheology over the entire region of measured shear stresses (Figure 15.1), but at sufficiently high shear stresses, Eq.(2), it predicts unrealistic viscosities lower than that of the paraffin oil, $\bullet_p$. For this reason, it was assumed that Eq.(2) is valid for $\tau \leq \tau_s$, where $\mu(\tau_s) = \mu_p$, while $\mu = \mu_p$ for $\tau > \tau_s$.

An artificial 2D single fracture (dimensions: 150 mm x 110 mm) of controlled morphology (Figure 15.2a) was fabricated by etching mirror image patterns of a chamber-and-throat network on two glass plates with hydrofluoric acid, and sintering the glass plates in a programmable furnace (Avraam and Payatakes, 1995). The cross-sections of pore chambers and throats were eye-shaped (Figures 2b,c) and for flow studies, they can be approximated as ellipses. The pore dimensions of the artificial fracture are comparable to the corresponding measured ones of real fractures (Klint and Tsakiroglou, 2000). The chamber diameter ($\langle W_C \rangle = 600\mu m$, $\langle \sigma_C \rangle = 150\mu m$) and throat width ($\langle W_T \rangle = 160\mu m$, $\langle \sigma_T \rangle = 40\mu m$) distributions were determined by estimating the relative variation of the pore sizes due to etching and sintering processes (Tsakiroglou and Payatakes, 1998). The pore depth distribution ($\langle W_P \rangle = 140\mu m$, $\langle \sigma_P \rangle = 10\mu m$) was estimated with reference to earlier measured ones and by matching the calculated absolute permeability of a theoretical pore network to the measured one of the glass micro-model, as explained below.

Non-Newtonian NAPL flow experiments were performed on an artificial fracture (Figure 15.2a), at constant temperature, by adjusting the flow rate of injected NAPL, Q, with a syringe pump and measuring the pressure drop, ΔP , along a length, L, of the fracture with pressure transducers. The absolute permeability, k, of the fracture was determined by injecting Newtonian NAPL (paraffin oil), and fitted to the (linear) Darcy's relationship:

$$Q = \frac{Ak}{\mu L}\Delta P \quad (3)$$

where A is the (apparent) cross-sectional area of the fracture, defined by:

$$A = WP_l \quad (4)$$

where W is the total width of the fracture and P_l is the length of periodicity, thus the constant distance between the centres of two adjacent chambers (Figure 15.2a).

15.3 Theoretical flow of a fluid

15.3.1 Flow through a pore

The calculation of average flow velocity of a non-Newtonian fluid through a pore of arbitrary shape requires the simultaneous solution of the Navier-Stokes and rheological constitutive equations (Bird et al., 1977). Except for the most simple pore geometries and axisymmetric flows, this approach commonly results in a complex mathematical model that can be solved only numerically. Since the goal has been the modelling and simulation of non-linear flows in interconnected networks of numerous pores, a large number of runs and iterations would be required before obtaining results with satisfactory accuracy.

Alternatively, the average velocity, U, of the flow of an inelastic, incompressible time-independent non-Newtonian liquid through a pore of arbitrary cross-section can approximately be described by the modified generalised Rabinowitsch-Mooney equation (Kozicki et al., 1966):

$$\frac{2U}{r_H} = \frac{1}{a}\tau_0^{-b/a}\int_0^{\tau_0}\frac{\tau^{b/a}}{\mu}d\tau \tag{5}$$

where r_H is an hydraulic pore radius defined as the ratio of the area to the perimeter of the cross-section, a and b are geometric parameters depending exclusively on the shape of the flow cross-section (Kozicki et al., 1966), and τ_0 is the average shear stress at the wall, given by:

$$\tau_0 = \frac{1}{c}\oint_c \tau_w ds = r_H\left(-\frac{dP}{dx}\right) \tag{6}$$

The foregoing equations allow us to develop analytical (though approximate) solutions about the flow of non-Newtonian fluids through pores of complex geometry.

By assuming that the fluid rheology is described by a Meter model, introducing Eq. (1) into Eq. (5), and after some manipulation, the volumetric flow rate, Q_i, is obtained through a pore, i, as a function of the constant pressure difference, ΔP_i, imposed along its length, L_i:

$$Q_i = g_{0i}\Delta P_i + g_{1i}\Delta P_i \sum_{k=0}^{\infty}\lambda_{k1i}\left(\frac{\mu_R \xi_i \Delta P_i^{n-1}}{1+\mu_R \xi_i \Delta P_i^{n-1}}\right)^{k+1} \tag{7}$$

where, ξ_i, λ_{k1i} (k=0,1,2,3,...) are parameters of pore geometry and NAPL rheology given by

$$\xi_i = \left(\frac{r_{Hi}}{\tau_c L_i}\right)^{n-1} \qquad \lambda_{k1i} = \frac{k!\left(\frac{b_i/a_i+1}{n-1}\right)}{[b_i + a_i + a_i(n-1)]\prod_{j=0}^{k}\left(\frac{b_i/a_i+1}{n-1}+j+1\right)} \tag{8}$$

where $\mu_R = \mu_\infty/\mu_0$, whereas g_{0i} and g_{1i} are hydraulic pore conductance given by

$$g_{0i} = \frac{A_i\, r_{Hi}^{\,2}}{2(a_i+b_i)\mu_0 L_i} \tag{9}$$

$$g_{1i} = \frac{A_i\,(1-\mu_R)\,r_{Hi}^{\,2}}{2\mu_0\,\mu_R\,L_i} \tag{10}$$

respectively, where A_i is the pore cross-section area.

Such an analysis can be repeated for the flow of a Mixed Meter and Power Law fluid Eq.(2) through a pore, to obtain:

$$Q_i = g_{0i}\frac{\Delta P_i}{1+c\zeta_i \Delta P_i^{\,n-1/m}}\left\{1+\sum_{k=1}^{\infty}\lambda_{k0i}\left(\frac{c\zeta_i\,\Delta P_i^{\,n-1/m}}{1+c\zeta_i\,\Delta P_i^{\,n-1/m}}\right)^k\right\}+$$

$$+\,g_{2i}\frac{\xi_i \Delta P_i^{\,n}}{1+c\zeta_i \Delta P_i^{\,n-1/m}}\left\{1+\sum_{k=1}^{\infty}\lambda_{k2i}\left(\frac{c\zeta_i\,\Delta P_i^{\,n-1/m}}{1+c\zeta_i\,\Delta P_i^{\,n-1/m}}\right)^k\right\} \tag{11}$$

where

$$c = \frac{K^{1/m}}{\mu_0 \tau_c^{\,1/m-1}} \tag{12}$$

$$g_{2i} = \frac{A_i\, r_{Hi}^{\,2}}{2(na_i+b_i)\mu_0 L_i} \tag{13}$$

$$\zeta_i = \left(\frac{r_{Hi}}{\tau_c L_i}\right)^{n-1/m} \qquad \lambda_{k0i} = \frac{k!}{\prod_{j=1}^{k}\left(\frac{b_i/a_i+1}{n-1/m}+j\right)}$$

$$\lambda_{k2i} = \frac{k!}{\prod_{j=1}^{k}\left(\frac{b_i/a_i+n}{n-1/m}+j\right)} \tag{14}$$

15.3.2 Flow through a single fracture

A theoretical two-dimensional square chamber-and-throat network was computer-aided constructed by using as input parameters the structural characteristics of an artificial fracture. The values of parameters A_i, a_i, b_i, r_{Hi} were calculated for each pore-throat by assuming elliptical cross-sectional shape. For the determination of the network permeability, a fixed pressure difference was imposed along one direction, and the flow of a Newtonian fluid was solved by formulating mass balances at each node of the network (Shah and Yortsos, 1995; Sahimi, 1996) (namely, by setting the algebraic sum of the flow rates of bonds adjoining to each node equal to zero), calculating the hydraulic conductance of the bonds for linear flow (namely, by omitting the second non-linear term of the right-hand of Eq. (7)), solving the resulting system of coupled linear equations with an iterative Gauss-Seidel method, and using Darcy's law, Eq.(3). The hydraulic resistance of each bond was calculated from the sum of the resistance of the throat and the resistance of the two connected chambers which were considered as equivalent capillary tubes with width and length equal to the half of their diameter. A mean effective pore throat length, P_{leff} ($P_{leff}<P_i$) was calculated so that the permeability of the network remained unaltered when the contribution of pore chambers to the total conductance of bonds was ignored.

For the solution of the flow of a Meter or a mixed Meter and Power Law fluid through a 2D pore network, Eqs. (7) to (14) were employed by introducing the effective length P_{leff}, into the calculation of conductance, g_{0i} ,g_{1i}, g_{i2}, Eqs.(9), (10), (13) and ignoring the conductance of pore chambers. The mass balances resulted in a system of coupled non-linear equations which were solved at progressively increasing values of the imposed pressure difference •P along the network, by using a modified Newton method into an iterative Gauss-Seidel scheme (Pachner, 1984).

Phenomenological models can be developed with the aid of the effective medium approximation (EMA) as applied to non-linear conductors (Sahimi, 1993). For the flow of a Meter fluid through a pore network, a differential conductance, σ_i , is assigned to each bond according to the relation:

$$\sigma_i = \frac{dQ_i}{d(\Delta P_i)} \tag{15}$$

whereas EMA is expressed by the relation:

$$\int_0^\infty \frac{\sigma_i - \sigma_m}{\sigma_i + \sigma_m (z/2-1)} G(\sigma_i) d\sigma_i = 0 \tag{16}$$

where σ_m is a mean effective value, z is the network co-ordination number (z=4 for square lattices), and $G(\sigma_i)$ is the bond conductance distribution function. Homogenizing the pore network with the aid of Eqs.(15) and (16), allows the following to be obtained:

$$u = \frac{A_m r_{Heff} \varphi \tau_c}{2\mu_0 P_{leff} P_l} \left\{ \frac{1}{(a_m + b_m)} + \frac{(1-\mu_R)}{\mu_R} \sum_{k=0}^{\infty} \lambda_{k1m} \left[\frac{\mu_R \varphi^{n-1}}{1+\mu_R \varphi^{n-1}} \right]^{k+1} \right\} \tag{17}$$

where u is the superficial flow velocity in the pore network, and φ $\Delta P/L$ is a dimensionless pressure gradient defined by:

$$\varphi = \frac{r_{Heff} \Delta P}{\tau_c L} \tag{18}$$

Likewise, the following phenomenological model is obtained for the flow of a mixed Meter and Power Law fluid in a pore network:

$$u = \frac{A_m r_{Heff} \varphi \tau_c}{2\mu_0 (a_m + b_m) P_{leff} P_l (1 + c\varphi^{n-1/m})} \left\{ 1 + \sum_{k=1}^{\infty} \lambda_{k0m} \left[\frac{c\varphi^{n-1/m}}{1+c\varphi^{n-1/m}} \right]^k \right\} +$$

$$+ \frac{A_m r_{Heff} \varphi^n \tau_c}{2\mu_0 (na_m + b_m) P_{leff} P_l (1 + c\varphi^{n-1/m})} \left\{ 1 + \sum_{k=1}^{\infty} \lambda_{k2m} \left[\frac{c\varphi^{n-1/m}}{1+c\varphi^{n-1/m}} \right]^k \right\} \tag{19}$$

15.4 Discussion

The calculated superficial velocity - pressure gradient relationships for the flow of a Meter fluid and a mixed Meter and Power Law fluid of varying rheology (Table 15.1) in a 2D chamber-and-throat network, having the structural characteristics of an artificial fracture (Figure 15.2a), agree satisfactorily with experimental results (Figure 15.3a,b).

It should be noted that the mixed model is capable of predicting the power law flow behaviour at intermediate velocities (Figure 15.3b), whereas the Meter model accounts for the gradual change of shear viscosity toward an asymptotic constant value at high velocities (Figure 15.3a). The flow velocity / pressure gradient relationships almost coincide with the linear Darcy's law at very low velocities, becoming non-linear over low and medium velocities and gradually tending again to the linear Darcy's law at relatively very high velocities. This behaviour is completely consistent with the rheology of the synthetic NAPL (Figure 15.1) which appear as non-linear fluids at low and medium shear stresses, becomes quasi-linear (power law fluid of small slope, $m<1$) at high stresses, and linear (Newtonian) at very low and very high shear stresses, respectively.

All coefficients involved in Equations (17) and (19) depend explicitly on microscopic properties of the fracture and rheological parameters of the fluid. The effective radius, r_{Heff}, was found not to be sensitive to the Meter fluid rheology (Figure 15.3a) and weakly dependent on the mixed Meter and Power Law fluid rheology (Figure 15.3b). The phenomenological models expressed by Equations (17) and (19) agree satisfactorily with the numerical simulations and experimental measurements (Figures 15.3a,b). Both models can be combined with rheometric

data of NAPL and structural properties of fracture aperture to estimate the spatial and temporal migration of liquid pollutants within fractured formations.

15.5 Conclusions

Synthetic organic NAPLs have been prepared by dissolving wax in paraffin oil and their rheological properties modelled with Meter and mixed Meter- and Power Law fluids. Experiments of the 1-phase flow of NAPLs were then performed on artificial fractures etched in glass, such that superficial velocity-pressure gradient relationships have been produced. The flow of a Meter and a mixed Meter- and Power Law fluid through a pore of arbitrary cross-sectional shape has been solved analytically, and used for the numerical simulation of the flow in a pore network. Two new phenomenological models have thus been developed for the flow of Meter and mixed Meter- and Power Law law fluids, respectively, by using effective medium approximation (EMA) as applied to non-linear conductors.

Acknowledgements

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Table 15.1. Parameters of Meter and mixed Meter-and-power law models for synthetic NAPLs.

Meter Model					
Parameter	1 %	2 %	3 %	3.5 %	4 %
μ_0	0.054	0.539	1.507	2.474	5.952
μ_∞	0.032	0.037	0.046	0.046	0.057
n	1.657	3.658	3.638	4.734	6.211
τ_c	0.267	0.192	0.280	0.645	1.242
Mixed Meter-and-Power Law Model					
Parameter	1 %	2 %	3 %	3.5 %	4 %
μ_0	0.046	0.681	1.369	2.443	5.578
n	3.356	3.816	5.973	5.530	8.021
τ_c	0.264	0.137	0.259	0.618	1.258
K	0.044	0.111	0.300	0.321	0.521
m	0.955	0.833	0.698	0.701	0.669

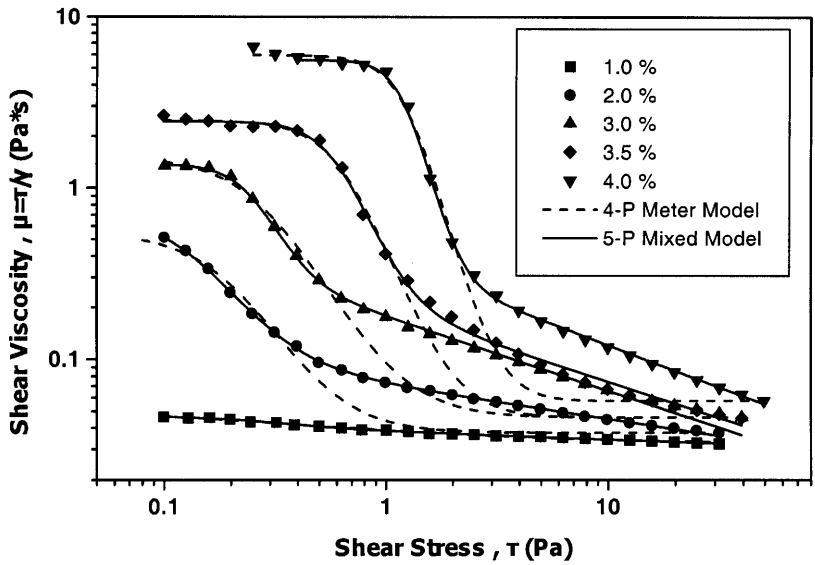

Figure 15.1. Experimental rheological data of NAPLs. Fitted curves correspond to fluid models

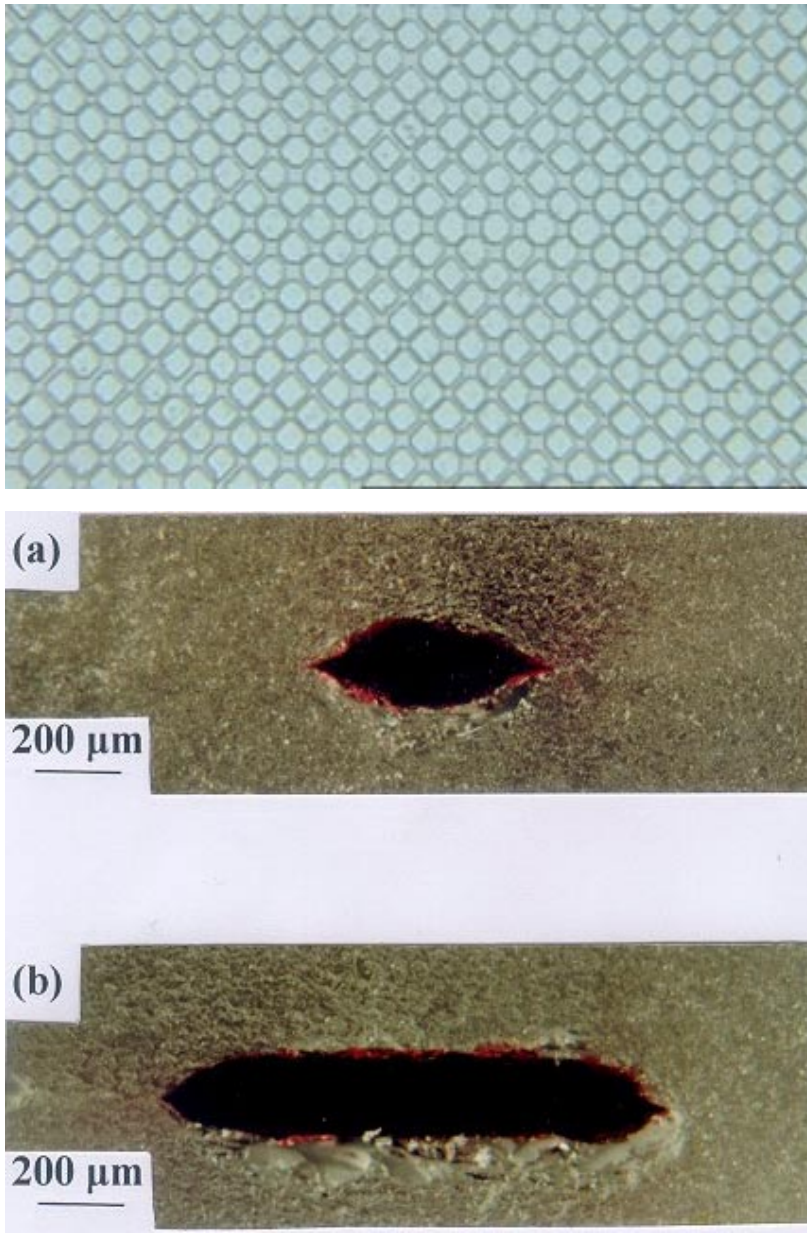

Figure 15.2. (a) portion of a glass-etched chamber and throat pore network, (b) cross-section of a throat, (c) cross-sections of a chamber

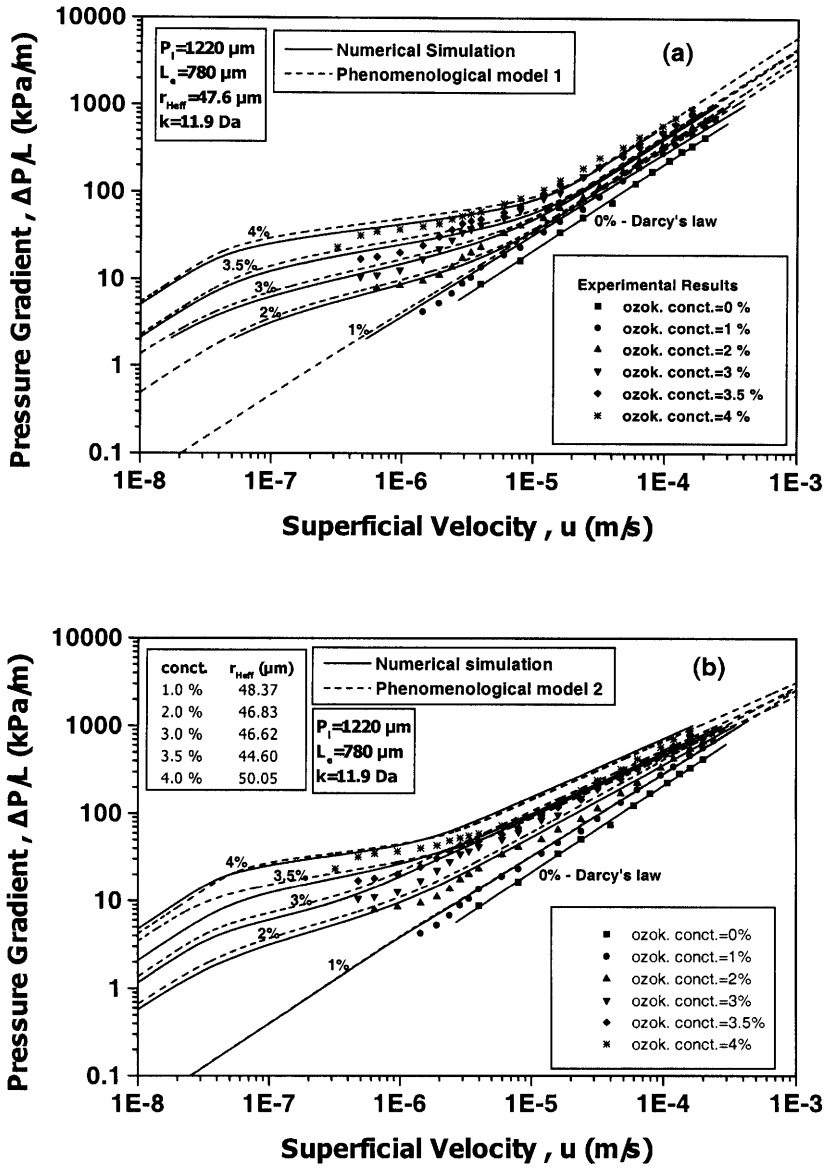

Figure 15.3. Comparison of experimental results of the one-phase flow of non-Newtonian NAPLs in artificial single fractures with numerical simulations and non-Darcian flow models based on (a) Meter, and (b) mixed Meter- and Power Law rheological models

16 Effect of strain-softening on settlement due to tunnelling in soft soil

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16.1 Introduction

In urban areas, tunnels for services and transport are usually excavated in the near-surface zone, which often exhibits poor geotechnical characteristics. In this case, the design of a tunnel requires ground deformations to be controlled so as to avoid damage to buildings and to ensure the safety of the workforce. Empirical methods of evaluating displacement caused by tunnelling have not always proved suitable in sensitive urban areas. The goal of this paper is to analyse the influence of strain-softening of soil on settlement due to tunnelling in soft ground by numerical methods.

16.2 Constitutive models

16.2.1 Mohr-Coulomb model

The Mohr-Coulomb model is a perfectly elasto-plastic model, conventionally used to represent shear failure in soils. This model is simple, and so widely used in geotechnics. The yield criterion of this model is defined as follows:

$$f^s = \sigma_1 - \sigma_3 \frac{1+\sin\phi}{1-\sin\phi} + 2 \cdot c \sqrt{\frac{1+\sin\phi}{1-\sin\phi}} \qquad [1]$$

and the tension yield function has the form:

$$f^t = \sigma^t - \sigma_3 \qquad [2]$$

where:

$\sigma_1 \le \sigma_2 \le \sigma_3$ (compressive stresses are negative)

ϕ = the internal friction angle

c = the cohesion

σ^t = the tensile strength

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The potential function is described by means of two functions, g^s and g^t, used to define shear plastic flow and tensile plastic flow, respectively. Function g^s corresponds to a non-associated law and takes the form:

$$g^s = \sigma_1 - \sigma_3 \frac{1+\sin\psi}{1-\sin\psi} \qquad [3]$$

and the function of g^t corresponds to an associated flow rule and is written :

$$g^t = -\sigma_3 \qquad [4]$$

where:

ψ = the dilation angle

16.2.2 Strain-Softening Model

This model is a development of the Mohr-Coulomb criterion with the non-associated flow rule described above. The difference lies in the possibility that yielding parameters, cohesion, friction angle, dilation angle and tensile strength are modified after the onset of plasticity as a function of the plastic portion ε^{ps} of the total deviator strain (ε_{dev}). They may harden or soften after the onset of plastic yield. The yield and potential functions are identical to those of the Mohr-Coulomb model.

Figure 16.1 shows the basic concept of the strain-softening model used. The linear portions define two parameters after yield, i.e. a softening portion in which the yielding parameters decrease linearly from the peak to residual, and a constant, residual portion in which the parameters only have the residual values. Figure 16.2 shows the parameters used after yield.

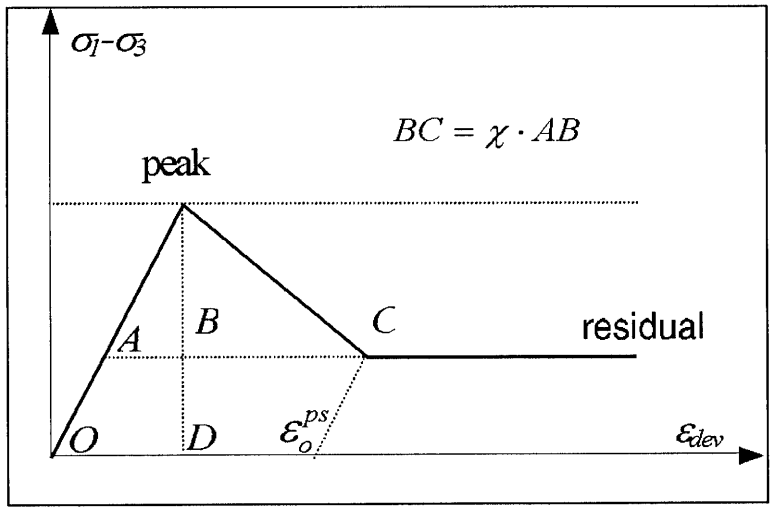


Figure 16.1. Strain softening model

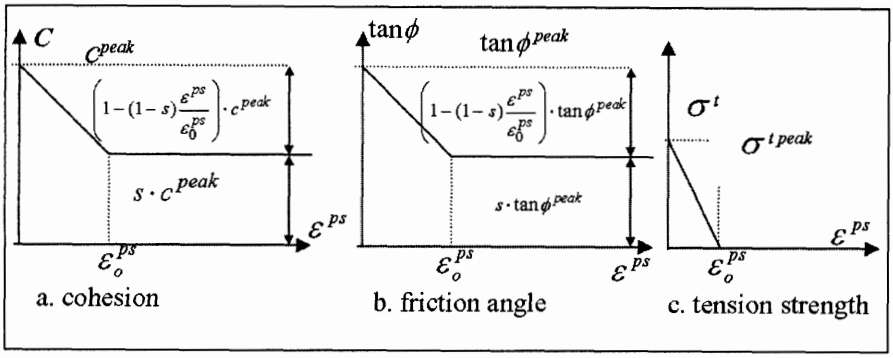


Figure 16.2. Yielding parameters defined

The following equations are used to define the softening of the yielding parameters:

$$\text{for } \varepsilon^{ps} = 0 \quad \begin{cases} c = c^{peak} \\ \tan\phi = \tan\phi^{peak} \\ \sigma^t = \sigma^{t\,peak} \end{cases} \qquad [5]$$

$$\text{for } 0 < \varepsilon^{ps} \le \varepsilon_0^{ps} \quad \begin{cases} c = \left(1-(1-s)\dfrac{\varepsilon^{ps}}{\varepsilon_0^{ps}}\right)\cdot c^{peak} \\ \tan\phi = \left(1-(1-s)\dfrac{\varepsilon^{ps}}{\varepsilon_0^{ps}}\right)\tan\phi^{peak} \\ \sigma^t = \left(\dfrac{\varepsilon^{ps}}{\varepsilon_0^{ps}}\right)\sigma^{t\,peak} \end{cases}$$

$$\text{for } \varepsilon^{ps} > \varepsilon_0^{ps} \quad \begin{cases} c^{res} = s\cdot c^{peak} \\ \tan\phi^{res} = s\cdot\tan\phi^{peak} \\ \sigma^{t\,res} = 0 \end{cases}$$

and to define the dilation angle the classical approximation is used:

$$\psi = \phi - 20^o \text{ , if } \psi < 0 \rightarrow \psi = 0^o \qquad [6]$$

where :

ε^{ps} = the cumulated deviator plastic strain

Based on equation [1], we can define the relation between *AB* and *OD*:

$$AB = \left(1 - \frac{\sigma_1^{res} - \sigma_3}{\sigma_1^{peak} - \sigma_3}\right) \cdot OD \qquad [7]$$

BC can be expressed as a function of AB, and it can be written as:

$$BC = \chi \cdot AB \qquad [8]$$

Hence, ε_0^{ps} can be defined as the addition $AB+BC$:

$$\varepsilon_0^{ps} = (1+\chi)\left(1 - \frac{\sigma_1^{res} - \sigma_3}{\sigma_1^{peak} - \sigma_3}\right) \cdot OD \qquad [9]$$

where:

σ_1^{peak} = the peak value of axial stress

σ_1^{res} = the residual value of axial stress

σ_3 = the confining pressure

The two constants, s and χ, can then be obtained from triaxial tests. This provides an axisymmetric condition test, from which the deviator total strain, ε_{dev}, and the deviator plastic strain, ε^{ps}, can be presented as:

$$\varepsilon_{dev} = \sqrt{\frac{1}{3}(\varepsilon_1 - \varepsilon_3)^2} \qquad [10]$$

$$\varepsilon^{ps} = \sqrt{\frac{1}{3}\left(\varepsilon_1^{ps^2} - \varepsilon_1^{ps}\varepsilon_3^{ps} + \varepsilon_3^{ps^2}\right)}$$

Based on the axisymmetric condition in the triaxial test, "OD" can be defined as:

$$OD = \sqrt{\frac{1}{3}\left(\frac{\sigma_3\left(N_\phi^{peak} - 1\right) - 2c^{peak}\sqrt{N_\phi^{peak}}}{2G_s}\right)^2} \qquad [11]$$

where :

$$N_\phi^{peak} = \frac{1+\sin\phi^{peak}}{1-\sin\phi^{peak}}$$

G_s = the shear modulus of the soils

c^{peak} = the peak value of cohesion

ϕ^{peak} = the peak value of the internal friction angle

16.2.3 Identification of parameters

The five parameters of the Mohr-Coulomb criterion model (E, ν, ϕ, c, and ψ) can be determined by conventional laboratory tests. Two additional parameters (χ and s) remain to be determined.

16.2.3.1 Parameter χ

Parameter χ can be identified by plotting deviator stress and deviator strain relations, as shown in Figure 16.1. Firstly, determine the value of "AB" and "BC", after which parameter χ can be determined, where χ = BC/AB. The average value of χ produced by different confinement stresses can be used.

16.2.3.2 Parameter s

Parameter s is the reduction factor to determine the residual strength of the soil. Two approximations can be used to determine this parameter. For the first model, consider the reduction parameter s to be the same for the internal friction angle as for the cohesion. In this case, decreasing values of internal friction angle and cohesion remain proportional. In this way the parameter s can be determined from:

$$S = \frac{\sigma_3 - \sigma_1^{res}}{2\left[\sqrt{N_c^{peak}}\right]} \qquad [12]$$

where:

$$N_c^{peak} = \left(c^{peak} - \sigma_1^{res} \tan\phi^{peak}\right)\left(c^{peak} - \sigma_3 \tan\phi^{peak}\right)$$

In the second model, the internal friction angle remains at the maximum value and the cohesion decreases linearly from the peak value to zero at the residual (c^{res}= 0). In this model Equation 12 becomes:

$$s = \frac{\sigma_3 - \sigma_1^{res}}{2\tan\phi^{peak}\sqrt{\sigma_3\sigma_1^{res}}} \qquad [13]$$

16.2.4 Validation of the model

The results of triaxial tests performed by Mohkam (1983) and Marsland (1971) have been used to illustrate the ability of the model to describe the strain-softening behaviour of sands and clays.

Mohkam (1983) carried out drained triaxial tests for the dense Hostun sand by using different values of confining pressure (0.10, 0.20, 0.40 and 0.60 MPa). According to these results, the peak value of the internal friction angle depended on

the confining pressure applied. In this case, the peak values of the internal friction angle varied from 45.3° to 37.9° for confining pressures between 0.1 MPa and 0.6 MPa. In the simulations, $\phi^{peak} = 40°$, $s = 0.883$ and $\chi = 40$.

Figure 16.3 shows simulation results using the triaxial test results of Mohkam for comparison with the model. The model (Figure 16.3a) produced an over-estimated deviator stress for $\sigma_3 = 0.6$ MPa, and an underestimated deviator stress for $\sigma_3 = 0.1$ MPa. For σ_3 equal to 0.2 MPa and 0.4 MPa, the model produced a close estimate.

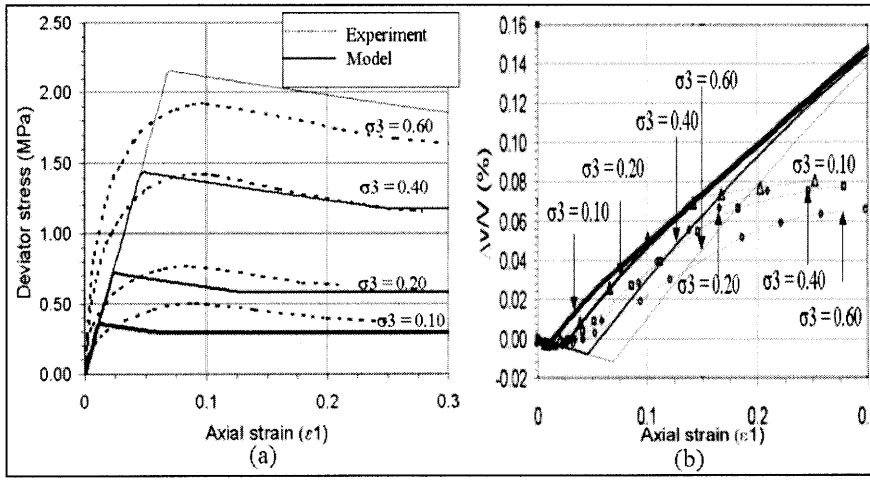


Figure 16.3. Stress-strain relations for drained triaxial test of Hostun Sand (Mohkam, 1983)

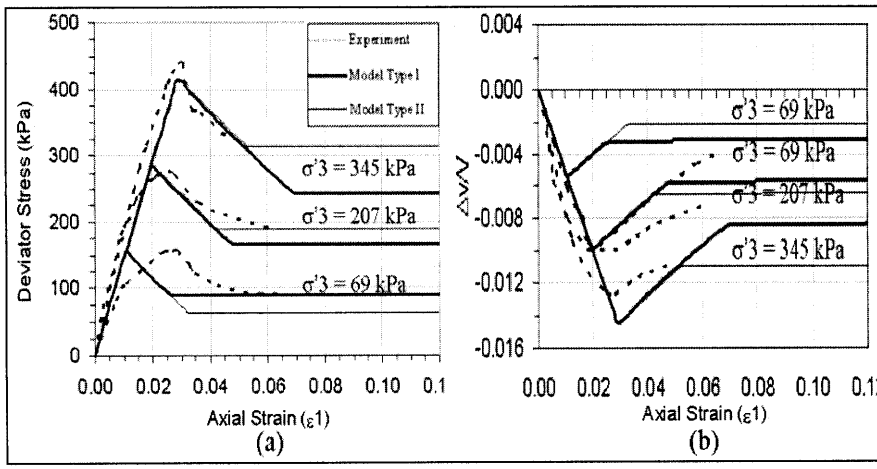


Figure 16.4. Stress-strain Relations for drained triaxial test of London Clay from Wraysbury (Marsland, 1971)

Marsland (1971) carried out similar tests for the fissured London Clay at Wraysbury, London. To simulate the fissured clays, the first model took $\phi^{peak} = 18.7°$ and $c^{peak} = 33$ kPa, $s = 0.645$ for the first model, s=0.973 whereas the second model took $\chi = 5$. The results are shown in Figure 16.4 and closely match.

16.3 Deformation analysis

16.3.1 Input Data

The case study has utilised data obtained from tunnelling for the French Lyon Metro line D, Gare de Vaise. Two tunnels were excavated from June 1993 to March 1995, beneath a residential area. The minimum cover of soil was one diameter of the tunnel (6.27 m) and the maximum was 15 metres. A summary of parameters used in the calculations is shown in Table 16.1.

To study the influence of strain-softening of the soil on the settlement on the ground surface, three types of reduction factor s were used (1.0, 0.75 and 0.50). Taking $s = 1.0$ represented the Mohr-Coulomb criterion. For parameter χ, only one type of χ was used (χ= 5) because, based on the simulation results, the influence of this parameter was not thought to be significant. This is the first model where the decreasing values of the internal friction angle and the cohesion are proportional.

Table 16.1. Parameters used in the input data

Items	Values
External diameter of the tunnel	$D = 6$ m
Elevation of the ground water table from the ground surface	-3.0 m
Elevation of the centre of tunnel from the ground surface	-13.34 m
Type of soils	grey silt
Elastic Young's modulus of the soils	$E_s = 6.0$ MPa
Poisson's ratio of the soils	$\nu = 1/3$
Cohesion of the soils	$c = 50$ kPa
Internal friction angle of the soils	$\phi = 22°$
Dilation angle of the soils	$\psi = 2°$
Thickness of the lining	$e = 350$ mm
Elastic Young's modulus of the lining (precast concrete)	$E_c = 13.5$ GPa
Poisson's ratio of the lining	$\nu_c = 0.20$

16.3.2 Computation procedure

To analyse the deformations induced by tunnelling, commercial finite difference software was employed: the Fast Lagrangian Analysis of Continua (FLAC). The model was implemented in FLAC using the fish function.

The usual 2D convergence-confinement method requires good evaluation of the initial deformation (U_i) or the initial deconfinement rate (λ_i) when the lining is installed. Usually this value is calculated empirically from an axisymmetric calculation using an elastic model or an elasto-plastic model; this can only take into account the last lining distance from the working face (Gesta, 1993).

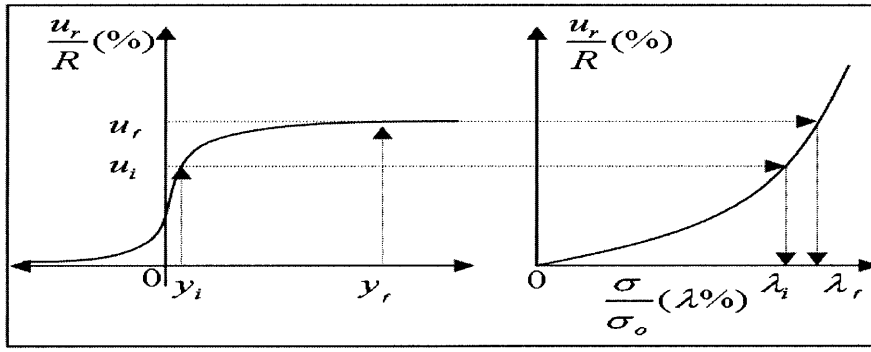


Figure 16.5. Definition of parameter λ

In order to analyse the interaction between soil and support, the value of U_i (in an axisymmetric calculation) when the lining is installed (location y_i) has been used. The confinement curve of the lining into the convergence curve of the soil can thus be plotted to obtain the final deformation (U_f) or the final value of λ (λ_f), as shown in Figure 16.5. This final value of λ (λ_f) in the plane-strain calculation can be used to predict the final deformations induced by tunnelling in the soil.

16.3.2.1 Convergence curve calculations

The convergence curve of the unsupported tunnel was derived by using the plane-strain model. Figure 16.6 shows the principal assumptions. The zero value of radial stress represents the condition along the tunnel wall excavation, with no support, the tunnel being assumed to be of infinite length. The stress applied at the boundary of the tunnel near the front face can be defined as $(1-\lambda)\sigma_0$. The initial state far enough ahead of the front face corresponds to λ=0.

The initial stresses used in this calculation are 0.2 MPa. The mesh used in the model, including the boundary conditions applied, can be seen in Figure 16.7. The model contains 25 zones in the x-direction and 25 zones in the y-direction. The stresses are considered to be axisymmetric stresses throughout this calculation.

The results (Figure 16.8) reveal the strain-softening behaviour of the soil affecting the radial deformation of the tunnel. From this it can be seen that the soil will behave as an elastic material until the deconfinement rate is equal to 70%; after that plastic behaviour of the soils is observed. The influence of the strain-softening of the soils only can be seen in the plastic zone, affecting the radial deformation of the tunnel. In the plastic zone, when the value of s decreases, the radial displacement will increase. Here the influence is not significant until λ reaches 80%.

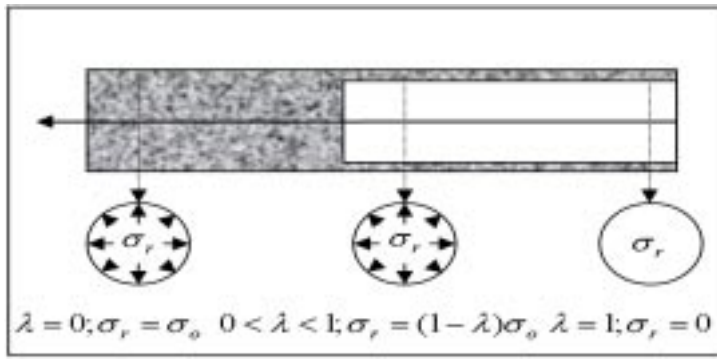


Figure 16.6. Virtual support pressures

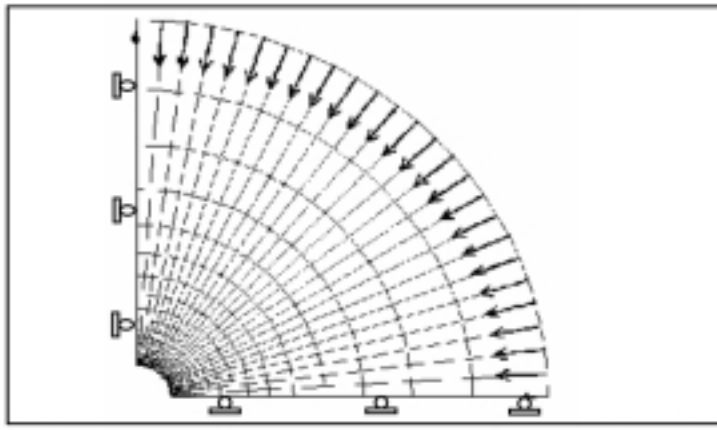


Figure 16.7. Mesh and boundary conditions used

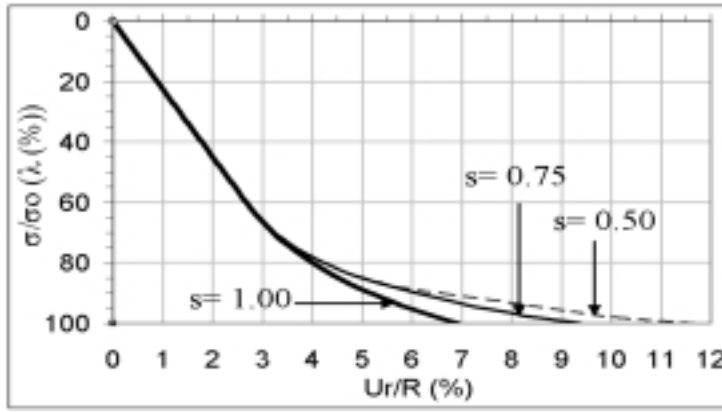


Figure 16.8. Normalized radial deformations versus the deconfinement rate for Mohr-Coulomb and Mohr-Coulomb with softening criterion

16.3.2.2 Axisymmetric calculations

Computation was then done by using the sequential excavation method (SEM) in the axisymmetric condition. The progress of the excavation is based on the length of one segment of concrete lining (1 metre). The last lining distance from the working face used was varied (d = 0.0, 1.0, 2.0 and 3.0 m). The initial stress used in the calculation was 0.20 MPa, the same as the overburden pressure at the centre of the tunnel in section P2 (near Place Dumas de Loire). The pressure on the working face was 50% of the initial stress. The mesh and the boundary conditions used in the model can be seen in Figure 16.9.

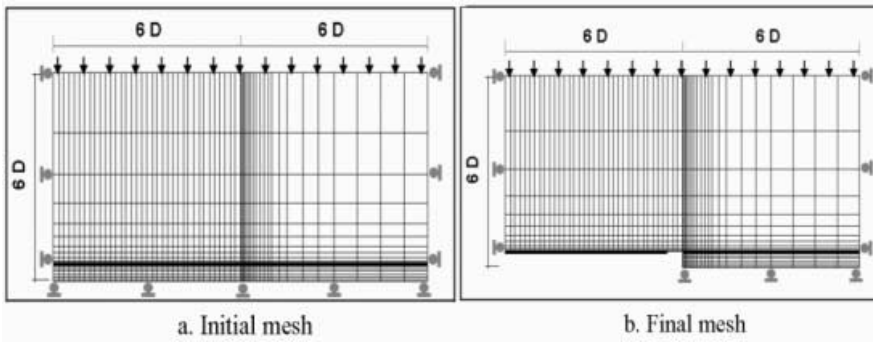


Figure 16.9. Mesh used in axisymmetric calculations

The initial deformation of the tunnel (U_i) was defined in this calculation, where U_i is the radial deformation at a distance y_i from the working face of the tunnel. This distance is defined as:

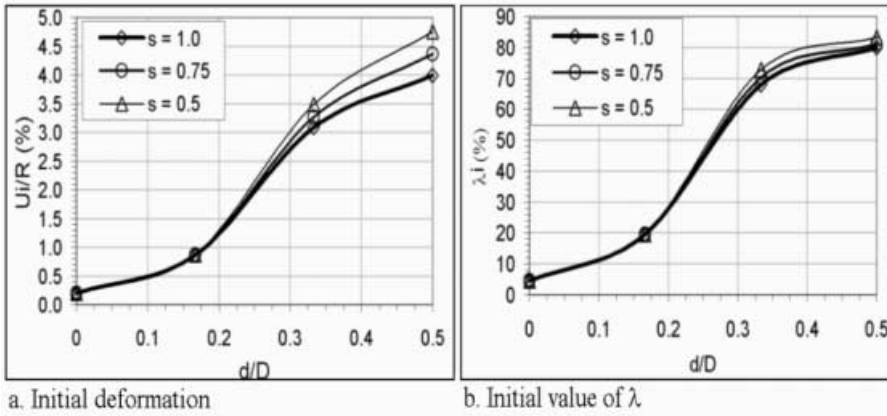
$$y_i = d - \frac{p}{2} \qquad [14]$$

where:

y_i = mean length of the non-supported zone
d = the last lining distance from the working face
p = the progress of the excavation

To obtain the initial value of λ (λ_i), the value of U_i could be plotted into the convergence curve of the soil. The results obtained from this calculation are shown in Figure 16.10. This clearly shows that the value of s and d will influence U_i and λ_i. When the value of s decreases, U_i and λ_i will increase; the values of U_i and λ_i will increase when the value of d increases.

In this case, the influence of s seems to be, not negligible but not very significant on the value of U_i, as can be seen in Figure 16.10a. Moreover, the influence of s does not significantly affect the value of λ_i even though this value will increase as the value of s decreases, but that increase is negligible when d/D = 0.50. The value of λ_i tends to be asymptotic as the value of d/D increases.



a. Initial deformation b. Initial value of λ

Figure 16.10. Initial deformation and initial value of λ when linings were installed

16.3.2.3 Confinement curves

The confinement curve of the lining or support depends chiefly on the geometrical and mechanical characteristics of the structural members. Here only a full-circle lining has been considered, exhibiting elastic behaviour. Thus the equation for the confinement curve (a straight line) for the elastic part of the strain is:

$$U = U_i + \frac{R}{k_c}\sigma_r \qquad [15]$$

in which the lining stiffness k_c (considering that the thickness of the lining is small compared with the radius) is:

$$k_c = \frac{E_c e}{(1-\upsilon_c^2)R} \qquad [16]$$

where :

E_c = the elastic Young's modulus of the concrete
ν_c = the Poisson's ratio of the concrete
e = thickness of the concrete
R = radius of the tunnel (i.e. the radius at the soil-concrete interface)

In Equation 15, the information from U_i obtained from the axisymmetric calculation is needed. The results of this calculation are presented in Figures 16.11, 16.12 and 16.13.

It can be seen that the last lining distance from the working face plays an important role in determining the initial radial deformation or the initial deconfinement rate. The value of s will only have an influence when the soils are in the plastic zone. In other words, it can be said that as long as the soils are in the elastic zone, the influence of strain-softening can be avoided. In this case the slope of the

confinement curve is almost vertical, because the stiffness of the lining is quite rigid, and the final value of λ is almost the same as its initial value.

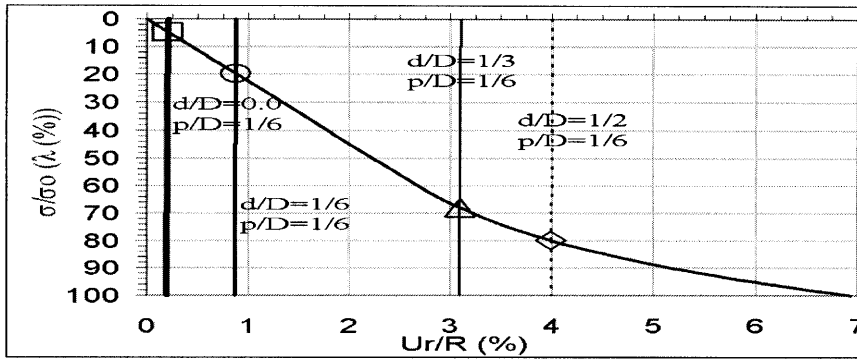


Figure 16.11. Convergence-confinement curves for Mohr-Coulomb criterion without strain-softening, s = 1.0

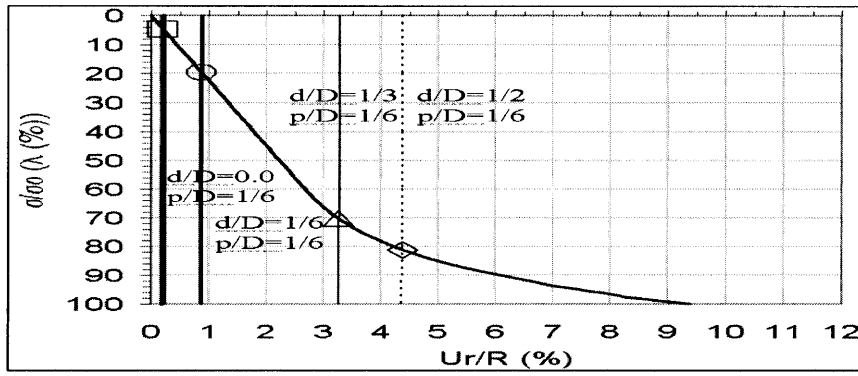


Figure 16.12. Convergence-confinement curves for Mohr-Coulomb with strain-softening criterion, s = 0.75

16.3.2.4 Deformation induced by tunnelling

Deformation induced by tunnelling may be derived from the plane strain calculation. The value of λ_{final} obtained from the convergence-confinement curves can be used directly. This is divided into five steps for d/D = 0.0 and 1/6, and eight steps for d/D = 1/3 and 1/2. The value of K_o used in this model equates to 0.50.

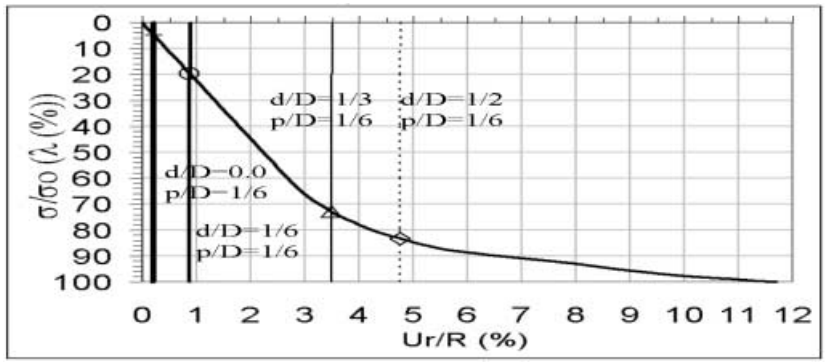


Figure 16.13. Convergence-confinement curves for Mohr-Coulomb with strain-softening criterion, s = 0.50

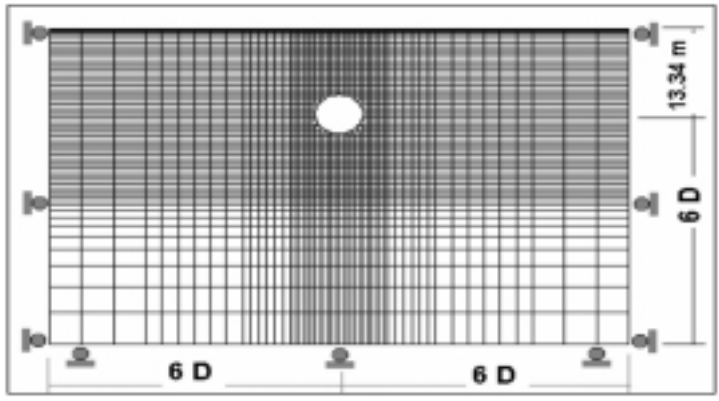
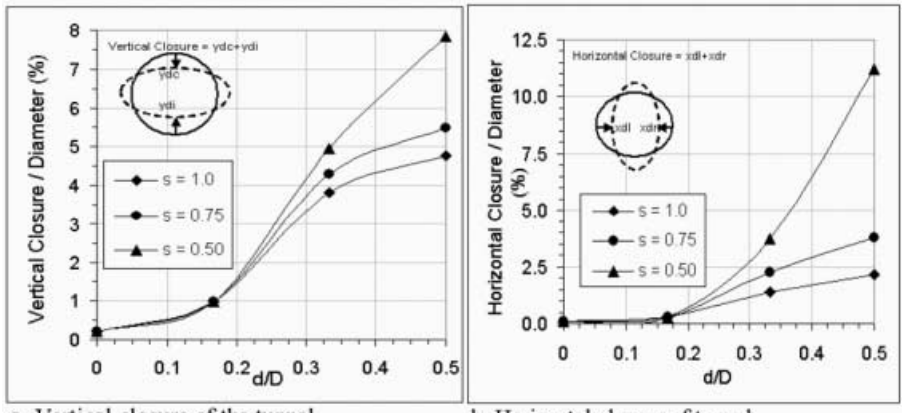


Figure 16.14. Mesh used in the settlement calculation

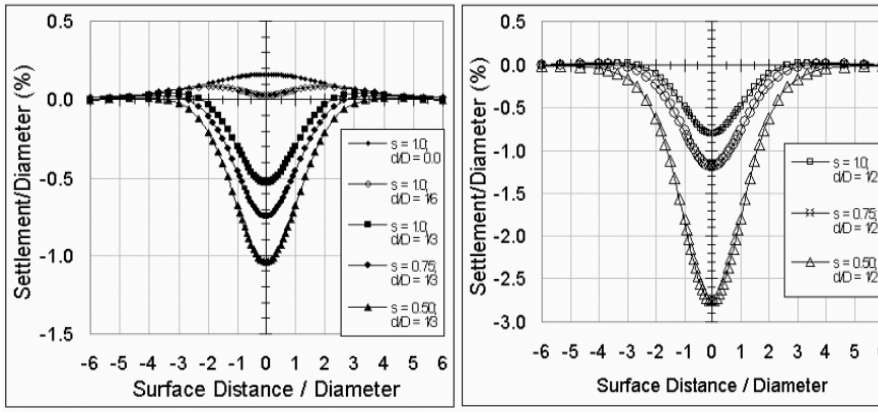


a. Vertical closure of the tunnel b. Horizontal closure of tunnel

Figure 16.15. Vertical and horizontal closure of the tunnel

The fixed displacement boundary was applied to the model at distance of 6 D from the centre of the tunnel. The mesh and the boundary conditions are shown in Figure 16.14.

Figures 16.15, 16.16, and 16.17 show the results for the plane strain calculation when the final value of λ is applied. The same phenomena can be seen in these figures, with decreasing value of s and increasing value of d/D, increasing the vertical closure, the horizontal closure and the settlement on the ground surface.



a. For d/D = 0.0, 1/6 and 1/3 b. For d/D = 1/2

Figure 16.16. Settlement on the ground surface induced by the tunnelling

The influence of the value of s can be seen in Figure 16.15. When s = 0.5, the vertical closure is more than 7% and the horizontal closure is more than 11%. Horizontal closures for s=1.0 and 0.75 turn out to be just 2.1% and 3.8% respectively. It can therefore be concluded that when s=0.5 and d/D=0.5, the soil is in the rupture condition.

In Figure 16.15, when s=0.5 and d/D=0.5, the horizontal closure is greater than the vertical closure, because the uplift pressure caused by water has reduced the vertical displacement.

It can be seen in Figure 16.16 that settlement on the ground surface increases as the value of s decreases. Settlement will increase also when the value of d/D increases. When the values of d/D are equal to 0.0 and 1/6, heaving will occur at the ground surface. This happens because the value of λ used is quite small, so the uplift pressure dominates. But when d/D is greater than 1/6, heaving on the ground surface will cease.

In Figure 16.17, it can be seen that settlement on the ground surface will increase as the value of d/D increases, notably when d/D=0.5. The settlement induced by tunnelling when s=0.5 and d/D=0.5 is 2.7%. This settlement is too great for an urban area because many buildings and services would be disturbed. To avoid this situation, when s=0.5 the value of d/D can be limited, i.e. the initial value of λ should be limited.

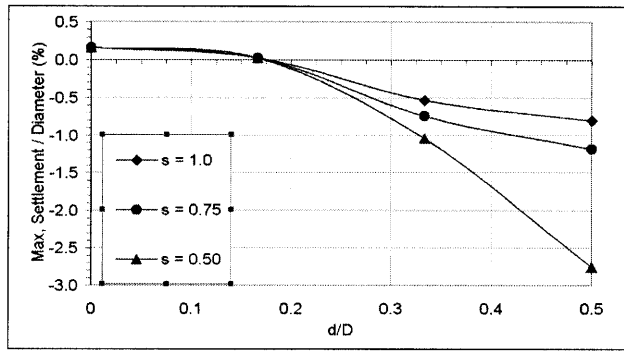


Figure 16.17. Normalized maximum settlement on the ground surface as a function of the distance to the last lining from the face of the tunnel

16.4 Conclusions

Predicting the effects of tunnelling with respect to ground deformation induced by strain-softening behaviour of the soil and the effects of sequential excavation has been accomplished.

It has been demonstrated that the influence of strain-softening in soil cannot be neglected, particularly when the reduction factor is quite big. This effect is not as important in the first phase when the lining is installed, but it is an important influence for the second phase calculation when considering the load transfer to the lining. This becomes significant where there is a large distance between the installation point of the lining and the working face, and could induce plastic deformation around the tunnel.

The results for the convergence-confinement method using the axisymmetric calculation and the plane strain calculation has shown that these provide an effective approach for analysing the ground-structure interaction situation and offer a systematic way of optimising lining design. This kind of calculation can be improved by using a complete 3D approach. However, this is a rather difficult calculation and the computation time will be long. In practice, the 2D analysis can be successfully used to develop a pragmatic solution.

The model presented is relatively simple, yet is able to give a good indication of the strain-softening behaviour of soil. This model requires just two additional parameters, both of which can be derived from the classical triaxial test.

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Part D Dissemination Strategies

Integration of modelling within decision-support systems is being spurred by the opportunities to disseminate models in new ways, thanks to the evolution of the Internet and Web-browser technologies, hardware and software developments, expanded information transmission capabilities, data visualisation, and improved data base concepts. Despite considerable research being devoted to subsurface characterisation over the past decade, the pace of technological innovation has outstripped the ability of many potential users to evaluate and adopt promising new characterisation methods.

Geological modelling is facilitated by using a set of mathematical models. These include topology (node connections), geometry (node locations) and feature properties (node attributes). This provides the basis for a "Shared Earth Model", a key vehicle for sharing subsurface knowledge between multi-disciplinary teams

Then there is the need to demonstrate that there is value for money in subsurface modelling. However, there is also the need for a longer term view, in order that the results of ground characterisation projects are not lost.

Experts need the ability to input interpretative points, perhaps utilising libraries of structural elements which can be used as interpretative points in a model. Cross-section (profile) construction is a good way of allowing a traditionally trained geologist to enter such information, but it needs verification. Can this be achieved using a computer?

The public increasingly wants information placed in context. This forms the basis of 'knowledge management' which recognises that:

'Knowledge' = 'Information' + 'Experience'.

To facilitate this, the geoscientist needs to be able to enter and disseminate information throughout the modelling process. The chief impediments to greater utilisation of subsurface geological modelling would thus appear to be:

- Lack of fully developed 3D and 4D oriented mathematical, cognitive, and statistical spatial analysis tools
- Inability of available systems to accurately depict the natural variability of geological features, or to represent uncertainties related to interpretation of spatial configuration or properties
- Lack of broad access to specialised tools for exploring and modelling geological systems, although many such tools have been developed for the oil industry, they are too expensive or commercially sensitive for all but a few organisations to procure; and
- Absence of comprehensive examples that might break the "scientific inertia". Many scientists know about quantitative subsurface characterisation methods, but do not embrace them because they wonder if the in-

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vestment in time, effort, and research funds to deal with the existing software tools will result in better science.

Visualisation is useful if it conveys information and not just depict the obvious. Retrieval of that which is pertinent is facilitated by digital management. The British Geological Survey digital geoscience spatial model (DGSM) has been developed in this spirit in an attempt to capture a whole knowledge base. The geoscience aspect includes all types of geological information, not just geology *per se* but also the 'spatial' aspect and time. This project has £4M funding over the next 5 years, and has a high institutional priority. The resultant modelling has already improved the data quality through enhanced understanding.

The biggest problem is verifying all the data once it is in digital form. Data must be screened for quality assurance, and often improved, before it can be used. As a result, discrepancies are now arising between outputs generated using data from the DGSM project and those derived from published geological maps. Dissemination of information about data sources, and about models based on data sources, must be distributed more easily and rapidly.

How can geological surveys and other providers of geoscientific information stay relevant in the digital era? They need to adapt to the changing demands, both technological and customer driven. There is also a danger of taking the geological survey for granted. There is a need is to create the right cultural environment, with appropriate finance and management arrangements in place.

The national geological surveys are no longer just map-making institutes. Customers want information that may not necessarily be map-related. Maps used to be the main tool for disseminating information, but this information is now often required in digital form, and GIS software such as ArcView is often used. Yet such 2D map-oriented systems are often insufficient. The only feasible way of providing information relating to any specific subsurface location is by use of a 3D model. The problem is that no single simple tool is available that supports widespread dissemination of very large 3D files. Perhaps there is a need to stimulate software manufacturers to produce such a tool. 3D models need to be available to users and are poised to overtake maps as the main output generated by a geological survey.

17 Dissemination of geoscience data: societal implications

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17.1 Introduction

Data and information may be suspect and politically contentious, at least occasionally. Lack of information may permit, in some eyes even justify, refraining from action. It may well be the case that decision makers tend to shy away from taking decisions because of the fear of adverse public reaction that their decisions might evoke; they may even prefer not to be confronted with information!

The worst situation arises when efforts are made to prevent unbiased information entering an otherwise biased debate. This may be illustrated by the following two examples drawn from the Netherlands.

Every ten years a national census is conducted to facilitate appropriate planning and policy formulation. Participation is compulsory and refusal to compile a return met with fines. The 1961 census resulted in two persons out of 11 million refusing. The following decade saw public debate on the role of the government and the issue of privacy, as a consequence of which 0.2% of the population refused to participate in the 1971 census. As the 1981 census approached, the government learned from opinion polls that at least 17% would refuse to participate. Subsequently the census was cancelled for 1991; a 2001 census was not even considered.

The consequence is a lack of reliable data concerning the composition of Dutch society since 1971 and any indication of trends. The result has been a dramatic increase in mistaken policy and misjudgements in political decision making. This was dramatically demonstrated when the El-Al Boeing crashed in Amsterdam in 1992; the actual population in the destroyed houses proved to be completely different from that which had been registered. Data collection through the use of a census had been declared politically incorrect and the consequent lack of data meant that the Amsterdam municipal archives could not be updated and thus planning was likely to have been inappropriate.

A second case concerns the public debate in the early 1990s relating to data collection for safety assessment studies to consider permanent storage of nuclear waste. On condition that no new data would be collected, the Dutch Ministry of Economic Affairs commissioned geological studies to establish the underground conditions of potential waste disposal sites in salt domes. Opponents of such stor-

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age feared that just the availability of new data might weaken their case, and that new data might lead to the conclusion that some of the salt domes could technically and/or environmentally be suitable for this purpose. The powerful green lobby in that time did not want to take that risk and successfully negotiated the restriction that no new geological data be collected for this purpose.

The general concept considers that, as long as there is no certainty about something, then there can be political freedom to take whatever action is deemed 'best'. In other words: availability of reliable data would constrain the political process or the options available to specific interest groups.

17.2 Data as a treasure

The current Dutch digital database for shallow boreholes alone holds some 400,000 borehole descriptions, worth more than 1 billion EURO. If this could be extended over the entire EU, the combined databases containing raw geodata would easily exceed a value of 25 billion EURO. This amount would be at least 100 times higher if the costs of all oil and gas boreholes and seismic surveys were to be included.

In general, the value of this treasure is not sufficiently well understood or appreciated, even by the government bodies who have funded the geoscience data acquisition programmes. Many Geological Surveys have assigned geodata management a high level of priority. Nevertheless they generally lack the means to allocate sufficient staff to this activity. Geoscientists certainly appreciate the relevance of quality assured geoscience data, but they are not well placed to do the job on their own. Neither would they like to see the costs required to be subtracted from their operational budgets!

Geodata is the key to revealing the third, downward, dimension; this increases in relevance day by day. Land value in urban areas continues to show a steep upward trend, leading to increased interest in developing subsurface facilities. Society is increasingly prepared to invest the higher sums of money required for development of underground space. However, the subsurface is still too often seen as a 'black box', even by engineers. To many, the subsurface is an unknown situation, containing unforeseen surprises and unpleasant discontinuities.

Those best placed to provide a reliable characterisation of the subsurface are the geoscientists. But in order to execute that task they need to have access to reliable geodata. The subsurface is a complex body, yet has formed as a result of natural processes that can be elucidated by appropriate investigation. However, any data acquired is just a sample of the complex subsurface reality. Thus the more data, the better its spread and quality, the more reliable will be the simulation of the reality.

The desirable end result is a 3D visualisation of the subsurface reality in a form that can be shown to colleagues, clients and the public (Figures 17.1 and 17.2). Such images require a thorough understanding of the subsurface, but their derivation can be made completely transparent. However, the geoscientist knows that what is displayed by (often bright and colourful) images may nevertheless be far

removed from reality. There is still no substitute for professional judgement based on relevant experience.

Figure 17.1. 3D visualisation of the subsurface reality using a bespoke computer projection display

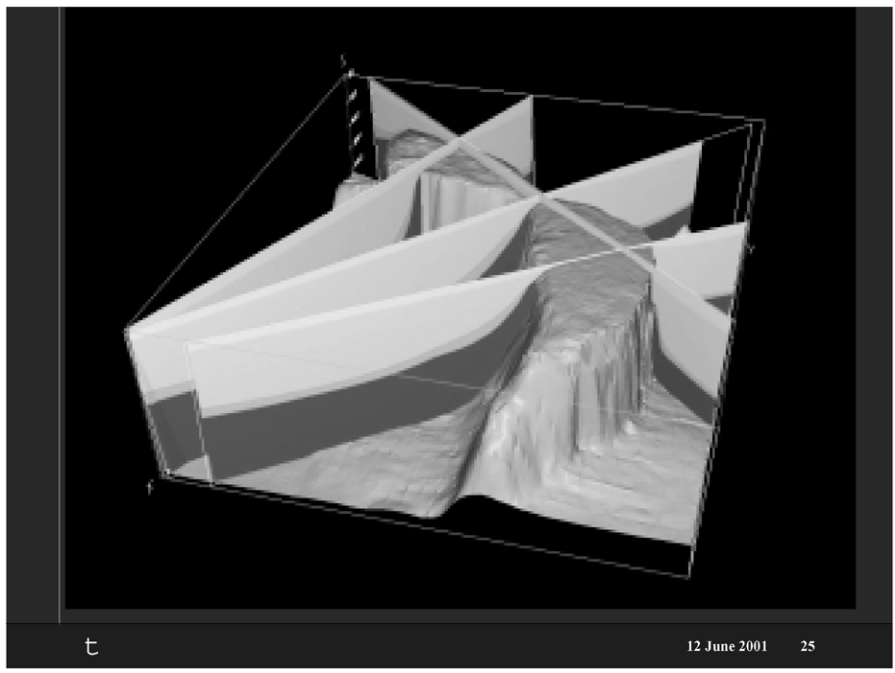

Figure 17.2. 3D projection and cross-sections to facilitate visualisation

17.3 Data collection and storage

Geoscience data collection generally takes a lot of time and there are many opportunities for introducing errors. Instead of using notebooks to write down descriptions of observations made on exposures or borehole cores in the field, geodata can be directly entered into portable field computers and electronically transmitted to a central database. (*Ed.* There is a separate debate regarding the wisdom of using classified schema for recording naturally diverse geological phenomena). Precise location using three co-ordinates for an observation site has equally been revolutionised by the introduction of GPS.

Once the electronic field data has been transmitted to the central database, the next step to be taken concerns Quality Assurance (QA). Data managers agree that QA is of the utmost importance for proper data management. However, QA is costly and tedious, although much of it can be assisted with the aid of appropriate software. Geoscientists generally do not consider QA an exciting prospect, preferring others to do this: outsourcing. However, the budgets available for the whole data management process are not generally sufficient for thorough QA.

Having collated and compiled the geoscience database, it is appropriate to make it available. Traditionally, dissemination is achieved through geological interpretation of raw data and compiling cartographically it as geological maps and cross sections. End users of geological maps require considerable specialist knowledge and they are of necessity restricted to being used by other geoscientists, thereby inhibiting knowledge transfer. However, such data stored in digital databases should be amenable to wider dissemination. GIS contains the tools to facilitate almost any kind of data storage and enable subsequent retrieval and display, at least in 2D. Thus any kind of product should be capable of being produced from a GIS, in forms suitable for a wide variety of end users. A 3D viewer further enhances the ease with which this type of facility can maximise the value obtained from the resultant images (discussed further in van Wees et al., *this volume*).

Attention will focus first on databases and their development by national geological surveys. Geoscience data is associated with a relatively small market and so there is only a restricted number of commercial database systems. Moreover, each geological survey is likely to wish to retain its own data terminology and framework, developed over many years to suit that nation's geology and geoscience data sources: boreholes, wells, measurement systems and data collecting devices, drilling equipment, organisation structure and operational management. All these factors may impact on the eventual database content, and the selected model, making it technically difficult to design a system suiting a large number of geodata users. However, the oil and gas industry through products such as Open Works (Landmark) and Finder (Schlumberger), have shown that this job can be done, at least for their own important subset of geoscience data. From a cost point of view, such systems are unlikely to be attractive to the majority of other geodata users.

A more computationally sophisticated option is the development of a portal. This is a Web application by which different database systems can be approached as if they constituted one big system. Data sets housed in different databases can

thereby be linked together and their contents communicated to other databases in the portal via messaging. Portals offer a promising way forwards, but their implementation faces serious problems due to the incompatibility of databases, especially if these have been derived from different organisations, each having their own data-structure. Communication between such incompatible databases within one portal will inevitably lead to loss of information.

The Dutch were faced with the necessity of reorganising their geodatabase system when they merged the National Geological Survey (RGD) with the non-governmental research institute TNO to form the TNO-NITG. A fresh start was considered to be the best option; substantial diversity existed among the 225 domains of geoscience information comprising groundwater data with databases that had been operational since the 1970's.

On-line delivery facilities had been introduced in 1986, and then new data was acquired from digital and analogue borehole descriptions, fossil data records and distribution charts, results of geochemical analyses, digital and analogue plots of grain size analyses, and digital map sheets. Some departments had stored their data in other ways, for instance spreadsheets, thus preventing free interaction within the organisation and obviating integral updating possibilities. A general problem arose with data that had to be compiled from paper, from floppy disks and filing cabinets, all at risk of experiencing data loss or mishandling, including the consequences of moving material to a new office.

One of the arrangements made by the Dutch government upon the creation of the new TNO-NITG was for the new body to be officially charged with the task of collecting, acquiring, quality controlling, archiving, analysing, interpreting and disseminating all data and information pertaining to the subsurface of the Netherlands and the Dutch sector of the North Sea, including its natural resources. In order to be able to perform this gargantuan data collection and dissemination task, four departments in the Dutch Government agreed to guarantee substantial financial resources on a long term basis.

The resulting data system was called DINO: Data and Information of the Netherlands Ondergrond. The aim has been to create a state-of-the-art integrated database with Internet access, capable of conducting the tasks of archiving, quality controlling and disseminating the data, and to support the other tasks of the new Institute's information function. This imposed a severe restriction to the functionality of the system: it could not contain geoscience applications for interpretation or analysis of the data for such purposes. Data would have be exported to external environments and the results of analyses and interpretation would subsequently be fed back into DINO. There was also a requirement to make the data continuously available to anyone in Dutch society. One positive aspect of this was that the complexity and size of the system would become so reduced that operation would be enhanced and reliability improved substantially.

Within the relatively simple DINO architecture, three major components can be recognised (Figures 17.3 and 17.4):

- The database itself, containing a high level of consistency checks on the data and on the operations performed on it within the database.

- A database maintenance layer, enabling maintenance forms to be displayed by data users on the screens of their desktop PCs. This layer includes report production, import and export control.
- A data dissemination layer accessible through a web site.

In the DINO database, the various different domains of geoscience data can be approached through individual databases: on lithology, on groundwater head, on groundwater quality, on well logs, on seismic records, on geochemical analysis data, on geotechnical data, on cone penetration tests, and on spatial data such as maps, structural models, property models, simulation models, reports and licences. All these databases can operate more or less independently. There is, however, a compulsory relation common to all databases with the location database, called Locator. Locator holds all the information concerning the location based on three co-ordinates. However, experience has shown that the where most serious errors originate from inconsistencies within the location data.

The web site, DINO*Shop,* acts as a one-stop-shop for geoscience data, complying with the requests of the Dutch government on funding the TNO-NITG programme. Clients are charged just for the marginal delivery costs. The philosophy adopted is that the data itself should be free of charge since the taxpayer has already paid for the geodata acquisition. By the end of 2001 DINO*Shop* could provide a simple alpha-numeric query facility, recognising the main attributes of the data entities. From April 2002 geographical queries will additionally be made available (discussed further in van Wees et al., *this volume*).

Data is delivered in a straightforward ASCII format as a zipped file. More formats will be added in the course of time. In October 2001 lithological data was made available in XML, a data delivery language of increasing importance that leaves open all options to the user concerning the final representation of the data: HTML, PDF, graphics, e-mail, spreadsheet, or just another database.

It is evident that developing such a database system and feeding it with a wealth of geo-information is extremely costly, and will take many years. Implementation of DINO exceeds the size of a conventional project and so may better be considered as an *endeavour*; the final costs will be balanced by significant corporate (or national) benefits, but these cannot be pre-determined. Current estimates for development of the initial software hosting all 225 domains of geoscience information, including the spatial information, require another five years and some 7 million Euro before it will be completed, which will not be earlier than 2006. Populating the databases with checked data will cost significantly more. It is anticipated that maintenance and updating the DINO software will require some 0.5 million Euro annually.

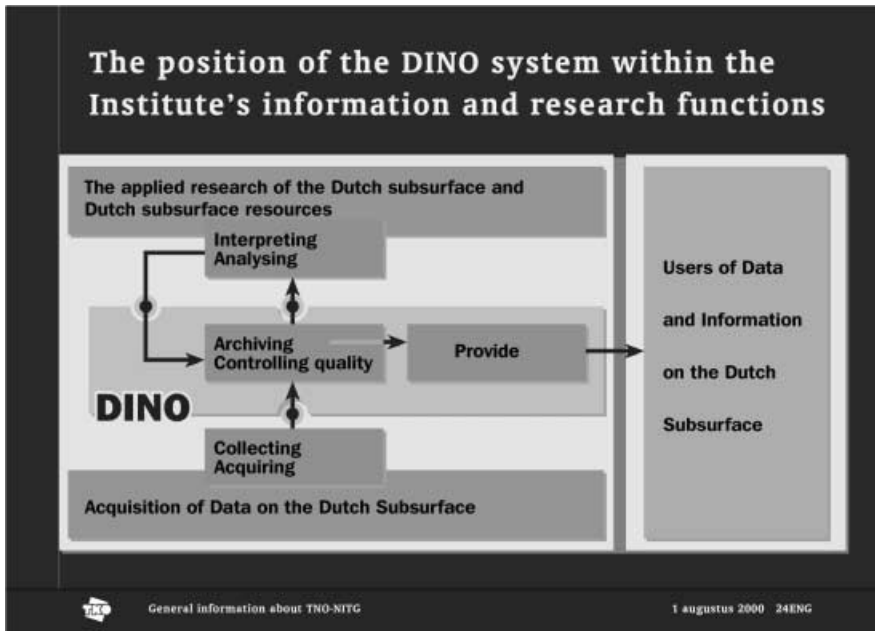
The position of the DINO system within the Institute's information and research functions
The applied research of the Dutch subsurface and Dutch subsurface resources
Interpreting Analysing
Archiving Controlling quality
Provide
DINO
Collecting Acquiring
Acquisition of Data on the Dutch Subsurface
Users of Data and Information on the Dutch Subsurface
General information about TNO-NITG
1 augustus 2000 24ENG

Figure 17.3. DINO within the Dutch information system

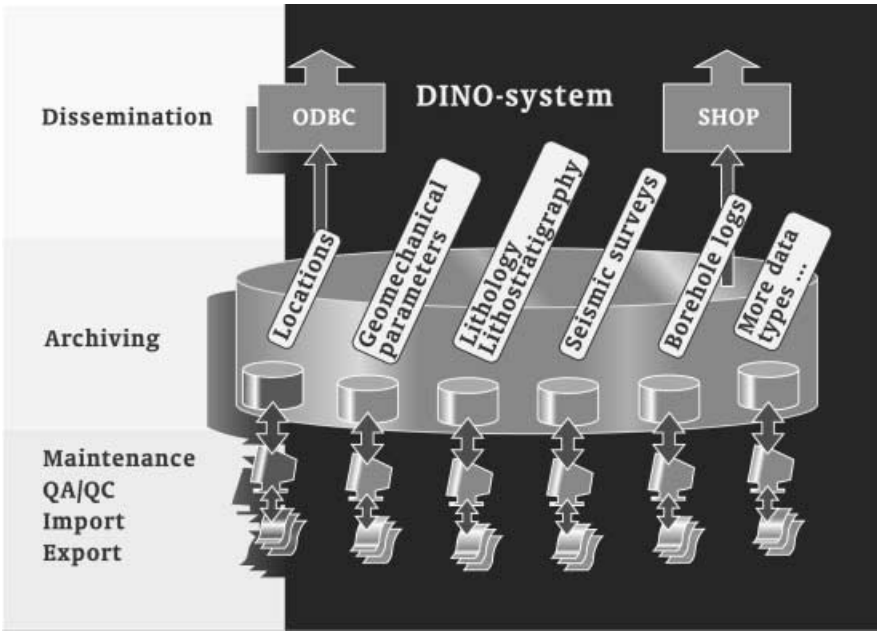

Figure 17.4. The basis of the DINO information system

17.4 Data dissemination in the European context

The societal impact of DINO is expected to be quite significant. Free public access to geoscience data, accompanied by an increased public interest, is expected to boost access demand for such data and hopefully too for aggregated information and geoscientific advice. Although data access will remain essentially free, institutes such as TNO-NITG will still need to raise funds for development, for instance earning money from advisory work.

Elsewhere in Europe, it may be noted that almost all Geological Surveys have databases, most of them digital or are in the process of being digitised. In 1998, an EU supported project was launched to connect such databases on a Meta-level. This project (GEIXS) has been quite successful. It is equipped with a Multilingual Thesaurus to cope with communication difficulties associated with the diversity of European languages.

The Multilingual Thesaurus comprises a database of some 7,000 terms in ten languages, and is continuing to be developed. Its creation has been steered by COGEOINFO, one of the Commissions of the International Union of Geological Sciences (IUGS) and a co-sponsor of the ESF conference which led to this book. Using this Thesaurus, the public can query the availability of geoscience data throughout Europe. Thus a Belgian contractor requiring a particular coloured rock slice for ornamental cladding could search the databases for dimension stone, in Flemish, within any EU country. GEIXS can be regarded as a 'clearing house' for geoscience information. GEIXS stimulates cross-border initiatives, as has already happened for the Pyritic Belt between Spain and Portugal. Environmental applications are likely to be a major beneficiary, for instance concerning the availability of aggregates.

17.5 Technical feasibility versus societal expectation

Databases have become an integral part of information management systems, serving as tools for decision-making at local and regional levels. Quite a number of such systems have been developed, but none of them have become commercially successful so far. One of the reasons is that society at large does not yet appear to be ready for the flow of information concerning the subsurface. Although digitising has progressed a long way, much data remains in analogue form. This makes provision of advice (consultancy) both time consuming and costly.

Another problem concerns data quality. As mentioned earlier, quality assurance and quality control of geodata has not yet become established. As a consequence, geoscience databases contain a mix of both good and poor data. This situation impacts in a negative way on the overall quality of the products generated from such databases, including maps and cross-sections.

Since decisions to be taken by planners and politicians can be no better than the data on which they depend, the likelihood of inappropriate judgement remains high. Society expects government decisions to be appropriately thought through

and based on the best possible data, aggregated into reliable maps and other products. If the geoscientific input proves to be incorrect, both the public and private sectors will lose confidence.

Geoscientists can only hope to acquire positive public perception if they are able to predict the impact of proposed developments or the occurrence of a selected geohazard correctly, in place and time.

Politicians have a different perspective: party political interests may be of overriding importance. There may be a belief that plans should not be spoiled by the presence of unfavourable information, or knowledge. Instead there is a tendency to gather information that appears supportive; this is at the expense of information to the contrary. Professionals operate in a difficult climate: on the one hand there is a requirement to ensure transparency, on the other there is the need to please line managers and clients.

A further factor hampering the free distribution of geoscience data is the possible impact it may have on the value of property, private or public. A geoscientist understands that a line on a map is the result of a geological interpretation based on a sample, but unless the whole area is dug up, one can never be sure about the exact position of such a boundary. However, members of the general public are more likely to interpret a line as the location of a certain boundary and make decisions accordingly. It is therefore vital that the quality of such a line be indicated, for instance by displaying reliability symbols. Thus if a house is situated close to an area of geological risk it will, of course, matter considerably to the owner precisely where the risk zones are situated. If no disclaimer is applied, there may even be a case for successfully suing the geoscientist or his organisation on the basis that the geological map is wrong and/or misleading. The onus on the geoscientist to prove he was right could be extremely difficult.

Organisations or companies collecting geodata may be reluctant to disseminate these to the public, with the potential for misuse or application by commercial competitors. The mere possession of a geo-database inherently means commercial advantage over those who do not have such information to hand. This has been offered as a reason by many geological surveys as to why they have been reluctant to open up their databases in the past. The cessation of industrial contributions would deprive the geological surveys of one of their main sources of information and put their very existence at risk.

Several developments in society have the potential to stimulate dissemination of geoscience data:

- Dedicated software packages are making the digital conversion of geodata faster and cheaper
- Geodata management organisations are opening up their files to enhance their visibility to the professional world and the public
- The educated public wishes to be informed about anything concerning their physical surroundings
- It is getting increasingly difficult to protect databases from hackers.

17.6 Discussion

It is anticipated that the reported trends will continue and that geoscience data will become increasingly freely disseminated, and become an accepted part of a increasingly transparent public decision making process.

Transparent public decision-making requires publicly accessible data. But producing basic data that are both accurate and reliable, and transforming such data into information that is transparent to the end-user, is not yet possible.

The end-users are the geoscientists' clients but they generally are not in a position to determine what data they actually need or want, nor are they well informed about the possibilities.

As for any business, data producers should interact with their clients. In addition to personal interaction, data producers need to develop practical methods and techniques for assisting their clients to establish their needs for geoscience data and information.

Data producers are generally not producing information that is transparent, either to the geoscientific or to other clients. The information derived from data, such as a geological map, is often not consistent, being strongly based on a set of unexplained or biased assumptions and, on top of that, delivered through a personal, sometimes even artistic, notion portrayed on a map displaying strongly coloured fields delineated by firm lines. Indeed, the one who produced the geo-information is perhaps the only person who is in a position to judge its validity. Whether or not this is a satisfactory state of affairs is debatable. New methods of extracting information from data need to evolve, starting with data collection. All subsequent steps require techniques and intermediate products that should be stored within an appropriate information management system. This is effectively calling for a knowledge management system. In addition, all the end-products should be labelled with their appropriate reliability level and comments concerning their validity.

Tuning the geo-information demand of clients, assisting geo-information production and making this transparent, constitutes a great challenge for the next decade. The necessity for rising to this challenge is pressing. There is a rapidly growing demand for space in already overcrowded cities. The availability of cheaper and safer tunnelling techniques ensures that the subsurface will become an increasingly significant target. The demand for sustainable development and construction, and sympathetic management of the environment, increases the need still further.

References

van Wees J-D, Versseput R, Allard R, Simmelink E, Pagnier H, Ritsema I, Meijers P (2003) Dissemination and visualisation of earth system models for the Dutch subsurface *[Chapter 20, this volume]*

18 An economic model for the dissemination of national geological survey products and services

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18.1 Introduction

Each national government needs efficient and timely access to quality-assured geospatial information concerning their country as a whole. Local government, society and the private sector cannot function effectively without liberal access to the geospatial information and knowledge acquired by government on behalf of their people. The elements of society that hold government and the private sector accountable, and seek concessions from them, may be defined as civil society.

The stipulation "country as a whole" implies that data models are considered in a manner that allows comparative analysis across the country. However, the geological and geo-political boundaries do not generally coincide, hence there needs to be a means of considering geospatial characteristics across national borders.

Most governments have established a range of national surveys to meet their geospatial information requirements. In almost all countries these have operated as natural monopolies in the regulatory environment of the public service (Coopers and Lybrand, 1996). Ubiquitous access to information and communication technology (ICT) and growing commercial availability of substitute products and services has raised questions concerning the regulatory constraints within which the Public Service continue to operate, and indeed to question whether the most effective environment has been created within which a national survey is tasked to meet modern geospatial access requirements, whether these be for government, civil society or the private sector.

Following the oil crisis of 1973, government deficits and national debts began to grow and many government institutions, including the surveys, became subject to frequent scrutiny and challenge, with the ultimate threat of privatisation. The surveys recognised that their organisations played a public interest infrastructural role, and sought solutions that preserved those aspects of national surveys of fundamental importance to the public interest. However, the clear and agreed principles, points of departure and business objectives necessary to negotiate their positions with central government agencies were in most cases inadequate.

Yet, over the last 15 years, geological surveys in a number of developed countries have succeeded in carving out new mandates and financing arrangements within a new regulatory environment which takes them outside the standard public

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service organisation. Examples are the British Geological Survey (BGS), Bureau de Recherche Géologique et Minière (BRGM) in France and the Netherlands geological survey (TNO-NITG). Such solutions make clear the distinction in organisation required for the various different products and services; there are tasks that should be carried out in the public interest and financed from government budgets, and other tasks that can be carried out jointly with, or in competition to, the private sector. In all cases outright privatisation has been rejected.

It has been found possible to generalise such solutions to create a model which describes:

(a) the requirements of economic efficiency in the pricing and dissemination of national survey materials (under the constraint that output be as large as possible in the absence of permanent subsidy, and that government is assured of unlimited access to the results)
(b) the consequences of these requirements for the management framework and corporate governance of National Mapping Agencies (NMA) (Groot, 2001)

If an appropriate expression of "the public interest" for a geological survey could be developed as a point of departure, the authors believe the findings could be extended to that type of national survey.

The issues raised have a special relevance to geological surveys in developing countries and countries in transition, which – in today's world of globalisation – struggle even more than those in developed countries. Many of these countries still rely on their natural resources as an important component of their economy. Often, their minerals industry is/ was state-owned and operated, and their geological surveys functioned as the exploration department of the State-owned Mining Enterprise. As the countries reform their mining sectors, the mandates of their geological surveys change and are increasingly questioned (IENIM, 1995). In addition, it is often virtually impossible for these organisations in today's world to train and keep their personnel due to the poor salaries they can pay them in relation to what the private sector (e.g. minerals industry) can pay. As a consequence, their staff capacity for fundamental data acquisition and management is limited as is their ability to keep up-to-date, let alone advise on investment issues for the nation (e.g. ITC and NITG, 1998).

Another issue relates to the changing role of geosciences in the modern world. The role of the geoscientist was traditionally to provide the expertise necessary to exploit large-volume resource deposits (reflecting the economies of scale) as a life-long employee of international mineral and petroleum companies. The geosciences were essential contributors to the creation of basic wealth. Over the last 15 years or so, there has been a shift to economies of efficiency: secondary recovery and smaller-size exploitation (Fisher, 1993; 1995). Such a change in the resource economy also requires a different approach from geological surveys.

Last, but not least, the geosciences have experienced an immense shift, from a focus on the exploitation of natural resources to the stewardship of the natural environment. This shift has affected the focus of many national geological surveys.

In this context the article addresses three questions:

- what is the political and economic justification of public investment in geological survey activities?
- what are the requirements for economic efficiency in pricing and distribution of geological survey products and services?
- what are the consequences of the answers to these questions for the management framework of geological surveys?

The answers to these questions make it possible to address the issue of privatisation or other regulatory environment, in a relevant context for geological surveys. The arguments have been developed using standard economic theory, especially from the field of the regulation of natural monopolies (Baumol et al., 1994, 1997).

18.2 The Public Interest

Governments need geospatial data, referenced and defined in the national context, to carry out their tasks. Examples are the allocation and management of natural resources, legislative and policy development for defence and for public safety, in support for a variety of regulatory activities, and general promotion of a better understanding of the physical, economic and human geography of the nation. In almost all national survey fields, national data standardisation must also take into consideration any international standardisation agreements.

At the most senior levels of government, high expectations have been expressed concerning the beneficial effects of the 'information society', or 'e-conomy', in diverse fields such as the delivery of health care, transportation management, lifelong learning, and sustainable development. The role of the private sector in providing the communications infrastructure and the so-called 'value-added' information services is strongly emphasised. Recognising that government itself is a very large source, as well as user, of such data, efficient and easy access to these sources becomes a high priority. Hence, expressions of policy often include measures that facilitate access to government-owned data (EC, 1994; 1998) (Executive Order 12906, 1994).

In this context the notion of sharing existing data through Geospatial Data Infrastructures (GDI) emerges as a significant matter of efficiency (Branscomb, 1982). Groot and McLaughlin (2000) define the purpose of GDI as facilitating access to and responsible use of geospatial data at 'affordable' prices. GDI is seen in this respect as a generalised concept which can be implemented at the enterprise level, the level of broad application domains such as coastal zone management, urban management or physical planning, or in the national context. Figure 18.1 shows the notion of GDI for the application domain of environment and physical planning.

On the right hand side of Figure 18.1 are the individual applications with their GI systems; all need routine supply of data. A Geospatial Data Service Centre (GDSC) harmonises/standardises all data for its application domain. It ensures that they are described in a national metadata standard, so facilitating the sharing of these resources by other potential users. The GDSC also enforces information

policies that control access, use and pricing, in keeping with legislation and overall government policy.

Generally speaking, national surveys are the relevant sources for the Framework Data. A special subset of Framework Data are the Foundation Data (FD): the fundamental geographical reference for all other thematic application data. National Topographic Surveys are usually responsible for producing, maintaining and distributing FD.

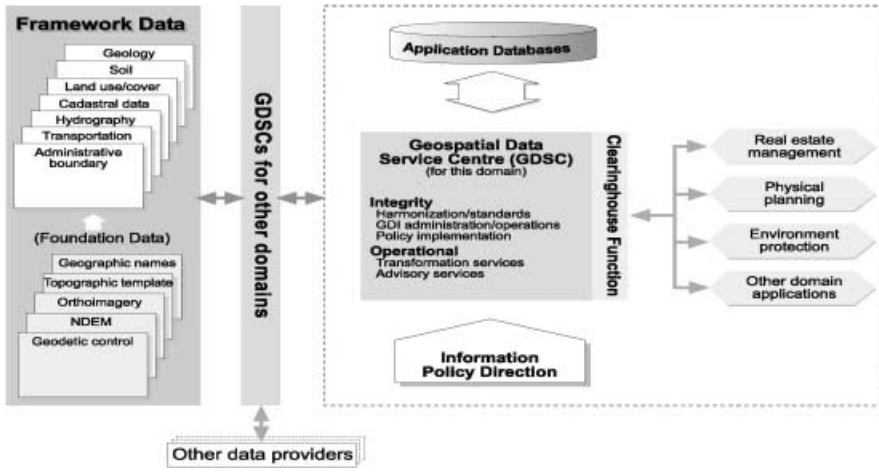

Figure 18.1. Geospatial Data Infrastructure serving the environment and physical planning application domain. (adapted from Groot and McLaughlin, 2000)

Within the context of the efficiency and effectiveness of government itself and the previously mentioned political expectations, optimal performance of national surveys and responsiveness to their client community becomes of paramount importance in exploiting the opportunities of GDI and thus reducing transaction costs to society.

Since their inception, national surveys have had a monopoly in the technological and industrial organisation of survey programmes. These monopolies have become increasingly challenged due to the combination of recent government reform and the growing proliferation of Information and Communication Technology (ICT). The client community has gained ubiquitous access to survey and geospatial data processing technology, as well as a growing supply of commercially available substitutes for the standardised topographic bases or thematic framework data sets (for example from Remote Sensing). Remote Sensing includes the Earth observation technologies from air- and space-borne platforms. National surveys have become confronted with new classes of user, interested in digital data for application in Geographical Information Systems (GIS).

To change the national survey perspective from automation to information provision is a major challenge that has had to be addressed, in order to respond to developing new markets and client-oriented processes.

Many national surveys have experienced major problems pushing through the regulatory restructuring and the business process redesign (BPR) to move to information provision. A major impediment has been the inability to specify what is considered to be in the Public Interest. The impact and opportunity offered by globalisation, ICT and the initiatives for government reform leads to the following expression of public interest (strategic goals):

- Governments must have unrestricted, guaranteed, efficient and reliable access to the knowledge and geospatial information of the country as a whole in order to carry out their tasks;
- Governments must facilitate the broadest possible access and use of its knowledge and geospatial information, to gain positive externalities and reduce transaction costs to society;
- Governments should strive towards zero subsidy to the users of its information to reduce the burden on the tax payer.

These points provide the basis for an institutional/regulatory environment and management framework within which the motivation and rewards exist for management to be responsive.

18.3 Economic characteristics of geological surveys

18.3.1 The assets

The assets of a geological survey are the results of decades of systematic geological inventory and mapping, research and reporting. Geological surveys also house the archive for a nation's natural resources. The assets include a critical mass of specialised, scientific and technical expertise, essential to maintaining the standards and specifications required, and to exercise effective stewardship.

With the exception of confidential field data and reports offered by exploration companies, outputs have generally been made available to the public at the cost of reproduction and distribution. These costs are negligible compared to the 'sunk cost' incurred in the process of creating these products. Sunk costs are those incurred in the past; these are irretrievable and therefore not relevant to current decisions. Sunk costs are a significant barrier to entry into an industry (Bannock et al., 1998). It is interesting to note, for example, that BRGM's mineral resources division generated 65% of its income in the year 2000 from service contracts, hence demonstrating that retrieving sunk costs from mineral resource mapping (not only in France itself, but also in its former colonies) have not taken place even after 200 years.

18.3.2 What constitutes the monopoly of a geological survey within an ICT environment?

Natural monopolies world-wide are subject to change because of changes in technology, and the market providing access to substitute products.

It is important to recognise that geological surveys approach their tasks in different ways, sensitive to inherent (significant) differences in the nature of their substrata. This has meant, for example, the evolution of quite different stratigraphical nomenclature. Depending on the importance of a certain domain, special agencies have been created for the collection and maintenance of data within that domain. For example, hydrogeological data are, in some countries, collected and managed by agencies other than the National geological survey. In the Netherlands, where most of the economic activity and most of the population is located in that part of the country that lies below sea level, geoinformation relating to coastal protection is the realm of both the National geological survey (TNO-NITG) and the Ministry of Transportation and Water Works and its institutes.

In terms of their regulatory environment, there are also distinct differences between different nations. The US geological survey (USGS) prides itself in being created by an Act of Congress in 1879 and in otherwise having a non-regulatory role, the most important other law pertaining to the organisation being the Freedom of Information Act. The USGS profiles itself explicitly as a user-oriented organisation, and organises an annual user conference. The USGS encompasses more domains than any other geological survey because aside from geology and mineral resources, both topographic mapping and biological resources fall under its mandate.

The USGS deserves particular attention, especially in light of its recent review (NRC, 2001). The mission of the USGS is: *"to supply information that contributes to the effective management of a variety of natural resources and that promotes the health, safety and well-being of the nation's citizens"*. The review committee focused on issues of content, personnel, budget and partnerships. The economy or legal status of the organization was not addressed explicitly, but a few issues can be read between the lines.

It recommends placing more emphasis on priorities of national scale (a.o. hazard and risk zonation, leadership in natural resource information) than is presently the case, and notes: *"Although responsiveness to customer needs should drive USGS priorities, this responsiveness should be in the context of the agency's national mission. The USGS should develop a more effective process to assess and prioritize customer needs"*. The review committee appears to be acutely aware of the challenge for the USGS of balancing between what society needs and what it asks.

The Netherlands Institute for Applied Geosciences/ National geological survey (TNO-NITG) is the Third National Geological Institute established in the Netherlands since 1903 and is part of an assembly of national R&D institutes TNO, for which a TNO-law has existed since 1985. TNO is an independent national organisation and is part of the public knowledge infrastructure. It has its own financial, personnel, commercial and R&D policies. TNO reports to the Netherlands Ministry of Education, Culture and Sciences, which appoints a Board consisting of

members of other ministries, such as that of Economic Affairs and Defence. The Ministry of Education, Culture and Science provides the organisation with core financing for so-called 'knowledge investments' (essential R&D).

The different elements of core financing together comprise about 20% of the gross income of NITG. Other ministries may also contribute, either structurally or incidentally (through contracts for special projects). NITG holds the nation's proprietary oil and gas data in archive and these are not accessible to the general public. NITG emphasises that it aims at making complete and reliable geological information accessible and available at minimal cost, especially through the Internet. Further discussions of these activities are presented by van Wees et al. (*this volume*). NITG otherwise engages in contract R&D against commercial costs.

The British Geological Survey (BGS) is legally part of NERC (Natural Environment Research Council). Some two-thirds of its income is channelled through NERC from the government, about one-third is from contract R&D.

In France, the BRGM (*Bureau de Récherche Geologique et Minière*) was created in 1959 as a successor to the *Service de la carte geologique de France*, which was created by the emperor Napoleon. The BRGM resides under both the Ministry of Research and that of Industry. BRGM has created its own way of dealing with issues of market and monopoly. It generated four independent companies together with private sector industries, each of which cater to a specific sector of the geoscience market.

A redefined monopoly leads to the identification of traditional survey activities, which can no longer be considered a part of the monopoly and could thus be carried out in the competitive market. The question then arises to what extent a geological survey can fairly compete in that market.

In summary:

- What constitutes the monopoly of a geological survey in the ICT environment?
- What role can a geological survey play in a competitive market for the delivery of products and services that can no longer be considered as part of the natural monopoly?
- How can a geological survey compete fairly in that market?

The outputs of the traditional geological survey were field data, collected and documented using internationally recognised standards and criteria, outcrop and borehole logs, resulting geological maps and their accompanying scientific reports. The point of departure for the definition of the present monopoly is, as in the past, the systematic survey component and its outputs. However, ICT, integration of survey technologies, database technologies, 3D modelling and visualisation have changed the methods of data collection, storage, representation and accessibility (Smith, *this volume*; Turner, *this volume*).

Whereas traditional geological maps effected both storage and representation of geological information and knowledge, today database technology and visualisation technology allows us to separate the two (Culshaw, *this volume*). Hence geological surveys need to redefine geological parameters in database terms and, based upon these databases, a variety of client- and task-oriented analyses and

visualisations become possible. NITG's DINO project (Data and Information of the Netherlands Subsurface) is a clear example of such an effort (e.g. NITG, 2001; de Mulder, *this volume*).

If the databases are defined in the monopoly as A(i) (i= 1....n), A could constitute the standard legend of a regional geological map at a scale of 1:50,000. Also assume that combinations of A(i) generate new market oriented products or services B(k)=f(A(i)) (k= 1...m). B can be considered, in a certain region, as being the information pertaining to specific stratigraphical units in the shallow subsurface, for instance aggregate resources that are suitable for road pavements. If the geological survey's monopoly is the generation and maintenance of A(i), then it would be reasonable, due to its monopoly ownership, to assume that it would also produce B(k).

It can further be assumed that there is market-demand for products and services C(l)=g(A(i);B(k);D(j)) which are combinations of products and services A(i), B(k) with data or information from other sources D(j) outside the monopoly. D(j) may be information concerning geotechnical properties of a specific shallow subsurface unit. These geotechnical properties may have been analysed by an engineering firm, interested in bidding for the excavation of a tunnel. This engineering firm may be prepared to provide commercial access to this information through a public Geospatial Data Infrastructure. With products A(i) and B(k) also being accessible by means of associated catalogues and metadata through the GDI, it becomes evident that interesting and beneficial competitive business activities can emerge, leading to new client focused products C(l).

D(j) may also include information generated by petroleum companies, on assumed-to-be-depleted petroleum reservoirs. The companies may have returned this information (perhaps including cores) to the public, i.e. to the geological survey, which may subsequently use, through contract research, the information to investigate strategic reserves at national and/or regional scale. Such research may lead to products C(l) indicating secondary recovery opportunities, which are of prime importance to the nation and the petroleum industry alike.

Hence, products C(l) can be delivered in the competitive market for geospatial products and services. If the geological survey wants to participate in this market and controls access to A(i) and B(k), the market can only be competitive and fair if a level playing field is provided to all competitors including the geological survey. Baumol's Parity Principle for Bottleneck Service Pricing (Baumol et al., 1994) gives the necessary and sufficient condition for this level playing field. It states that the geological survey must provide the products A(i) and B(k) to its competitors at the same price as it charges itself in the competition process.

It is unlikely that a geological survey, or for that matter any monopolist, would do so out of its own volition. Hence this condition needs to be enforced by a regulator. The simplest way of enforcing this is to make the products A(i) available at no cost.

18.3.3 Is it in the public interest to allow a geological survey to compete in the market for products C(l)?

If, as a result of the economies of scale of a monopoly, it is more efficient to produce product A(i), B(k) and C(l) together in the monopolist's facilities instead of separately in different companies, society benefits from these economies. Given the specialised know-how and capacity of a geological survey, it may become a successful competitor, although this is by no means assured (Groot, 2001). If the incremental cost of producing product C(l) together with A(i) and B(k) in the monopoly is smaller than the stand-alone cost of producing C(l) there are net gains to society called 'economies of scope'.

If the geological survey competes in this market, how would it be known if this provides the most efficient and economic approach? If the level playing field is enforced, as indicated above, the competitive process will decide automatically if economies of scope are being realised. If the geological survey wins in this process, then economies of scope are realised; if it fails, they are not and its competitor delivers the higher efficiency.

18.3.4 What should be the price-setting principles in relation to the strategic goals?

In this discussion it has been assumed that the 'sunk costs' are related to the creation of the first edition of maps, reports or databases and that these are not included in the price setting considerations. The cost of updating, maintenance and distribution would be considered as 'current running costs' in the price considerations.

The three strategic goals imply a strategic objective for the management of the geological survey – namely, this is to maximise output (as opposed to profit) of products A(i) (goal 2), subject to the constraint that economic profit cannot become negative (goal 3). This means ensuring the broadest possible use of the monopoly products A(i). The monopoly requires the price to be as low as possible but not so low that it requires continued government subsidy for the users of the products. This has implications for pricing and market segmentation.

Figure 18.2 demonstrates the difference in pricing under the constraint of maximising profit and maximising output. The condition for maximising profit is that the long-run marginal cost (LMC) equals the marginal revenue (MR). Hence, for a given technology, a monopolist would produce the quantity Q* for which the LMC is equal to MR. For that quantity, the demand curve indicates the price P*. Profit is indicated by the area Π. Maximising output would set production at the point where the demand curve (D) intersects the long run average cost curve (LAC), i.e. at Q′, for which a price P′ is indicated. Profit would then be zero; output would be raised by the lower sales price caused by scale economies. Shareholders in such a company would lose Π. If government is the sole shareholder, as would be the case of a geological survey, it may be willing to forego these profits in favour of providing lower cost access to the base-line data, and achieving the

positive benefits for society as a whole which would be generated by broader use of the data sets A(i).

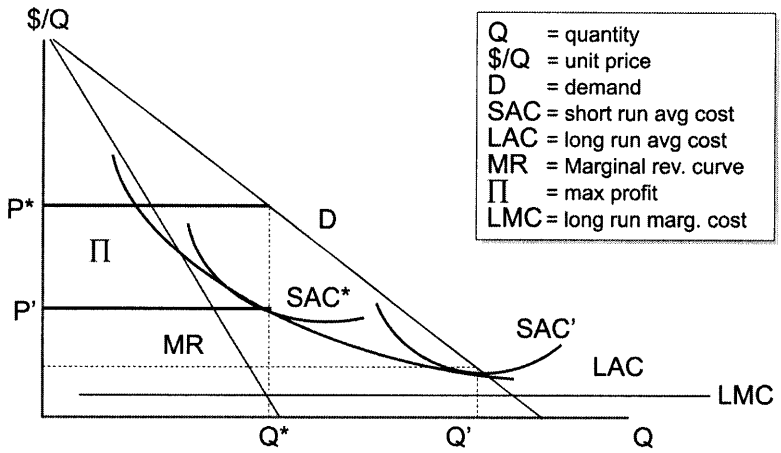

Figure 18.2. Maximising profit *vs.* maximising output with respect to monopolies (Frank, 1997)

How then should the products B(k) be priced? These are combinations of the products A(i). Earlier we assumed that it would be reasonable that a geological survey, using full cost recovery (including a charge for the maintenance costs of products A(i)), should produce these. It could even be considered fair if price discrimination is applied, implying negotiation on a case-by-case basis between the geological survey and the client (individual, public, private). As the development of products B(k) is entirely an internal matter for the geological survey it would be permissible to use the profits from sales to support the maintenance of the baseline data sets A(i).

Prices for products C(l) will have to be established as part of the competitive process on condition that it would not be permissible to subsidise this activity out of the monopoly by using profits from the development of products B(k). Furthermore, in developing the business plan for the geological survey, the profits from the competitive activity cannot be counted on to finance the maintenance of products A(i). Since the survey's success in the competitive market cannot be guaranteed. If a profit is made this could be invested in improving the technical infrastructure. This should improve the geological survey's efficiency, resulting in a lower long range average cost curve, so benefiting society as those efficiencies are passed on to the price of future sales of the products A(i).

18.4 Management

The third Strategic Goal is to achieve, in time, zero subsidy to the clients for procurement of products A(i). As this is the 'public interest set of products', in many

cases resulting from long-term data collation, it is important for government to make clear what it considers as costs that need to be recovered.

Sunk costs are opportunity costs incurred in the past; these are irretrievable. Hence most national surveys would make no attempt to quantify these costs for purposes of including them in the pricing structure. However, the costs that are subject to recovery are the maintenance costs and delivery of the products A(i). These are the costs associated with keeping data/ information/ knowledge current, with developing new insights into the geology and reflecting these in the products and delivering the product to the clients.

Maintenance can be achieved in a number of ways, such as through specific research projects or new analytical results arising from the production of products B(k). The cost of reproduction and dissemination/ delivery of the products to clients is, in almost all cases, very small compared to the value that the product represents, and almost zero for electronic delivery.

Imposition on management to achieve zero subsidy requires that there is a critical review of scientific, public interest and immediate (as well as longer term) economic aspects required to create new products A(i). The cost of maintenance will become an important consideration; this implies a future claim on budgets that will need to be recovered.

Will there be a continuing public interest and market? Experience of some national surveys suggests a preference for the weight of the scientific aspects, with too little emphasis on the financial commitments and economic consequences.

Hence the economic constraint on the monopoly pricing combined with a "towards no subsidy in five years" policy provides management with:

- the incentive to critically review the framework data and guard against unnecessary addition of information which is not essential to the effectiveness of the monopoly products;
- the motivation to be innovative and apply the most efficient combination of technologies and work processes to achieve the highest levels of efficiency possible.

It is also suggested that the signal sent out to the client community, that the products A(i) will not be available at zero or negligible cost, will engender discipline on the demand side for the products A(i). It is very difficult to get a realistic assessment of the value of a database or map if the potential user knows that their contents will be available at almost zero cost. *[Eds.: The issues concerned with converting data into information, and information into knowledge, go beyond the scope of such a simple economic argument]*

18.5 The role of regulation

Monopolies might benefit from a degree of regulation in order to ensure that they do not exploit their market power, for example by setting monopolist prices. Much has been said and written about this subject, addressing for example the degree of overkill and the high costs of regulation. See, for example, Posner (1969) for an

extensive critique of regulatory practice, or Baumol et al. (1994) who incorporate much international experience of standard regulatory mechanisms.

Baumol et al. (1997) suggest a bottom line for regulatory involvement, which appears to be applicable to National Mapping Agencies. They also present the principles of 'the new approach' to economic regulation:

"The sole purpose of economic regulation is to facilitate and encourage effective competition where feasible, and to provide an effective substitute for competition where that is not possible, at least for a substantial period. The underlying premise of the new regulation is that where competition is effective it can do a better job of protecting and promoting the public interest than any government agency. Therefore where, and only where, competition is either absent or too feeble to do the job, it is appropriate for the regulator to step in. But in doing so, the regulator's obligation is severely limited. It is to supply as near a substitute for the missing ingredient as can be devised, that is, to determine means to elicit the business behaviour that effective competition would have enforced if only it had been present".

In the context of the three strategic goals of government, it has been assumed that regulation of a national survey monopoly would only be required if the Survey intends to participate in the competitive market for those value-added geospatial information products and services which are based on the products in the monopoly i. e. products A(i) and B(k). This would suggest that the lowest level of independent regulation for the geological survey must focus on:

- the level playing field;
- desirable pricing behaviour (based on optimising output);
- banning cross–subsidy for the content and maintenance of the products A(i) from the commercial value-adding activities, products C(l).

The absence of comprehensive cost-accounting systems in government is an impediment to such regulation. The tax system may also sustain an unbalanced position. Thus how should the institutional environment be tailored to provide effective motivation and reward for achieving responsiveness to the (changing) client environment and furthering society's interests?

A number of points of departure and principles can be listed. These can define the management framework for a geological survey so that it would meet the three strategic goals of government with economic efficiency:

1. For public interest products A(i), the geological survey is a natural monopoly and operates to maximise output (Strategic Objective 2).
2. Prices for products A(i) should equal the Long Range Average Cost at a point where economic profit is not negative (Strategic Objective 3).
3. For society to benefit from the economies of scale and economies of scope, the geological survey must be allowed to compete in the value-added market segment. Following the bottleneck-service pricing (Baumol et al., 1997) principle, the geological survey would charge itself and competitors the price mentioned under 2, subject to regulatory supervision.
4. The geological survey must be constituted under corporate law, with business accounting and financial reporting requirements but no preferential tax breaks.

5. Financing the public interest products A(i) independently, ensuring there is no cross-subsidy from the marketing of their derived products.
6. Invest the profits from successful competition in the value-added market to further improve efficiency.
7. Practise price differentiation in the development of products B(k), with profits being invested in maintaining/improving products A(i).
8. Give sufficient, but limited, time to make the agency financially self-sufficient and cease being a burden on the taxpayer. This will require balancing complexity of content of the A(i) set of products and long run average cost (and, thus, price) in such a way that output is maximised.
9. Appoint an independent regulator with the powers to:

    - oversee the implementation of the 'level playing field';
    - ensure that there are no cross-subsidies from the value-added competitive segment of the market to the public interest products;
    - ensure that pricing is in sympathy with the requirement for maximising output, subject to the constraint of zero subsidy to be achieved in a defined and accepted time limit.

18.6 Regulatory reform

The principles and points of departure have now been stated which define an effective business environment for a geological survey in meeting the three strategic goals of government. It appears impossible to meet these goals under the normal regulatory environment of a public service. Any form of greater independence from public service and its incumbent regulations must serve the principles and points of departure that have been presented as pre-requisites for efficiency in meeting the three strategic goals.

Outright privatisation of a national survey would be folly. It would place the ownership of all data assets in private monopolistic hands, including the exclusive right to exploit these. Governments would thus lose all control over strategic information assets to which they need unlimited access to carry out their tasks. This includes the duty to the nation to enable attraction of investment, an issue that is especially important for those developing countries and countries in transition that (still) have a resource economy, and matters of national security.

It is also highly questionable whether any private enterprise would entertain a serious bid for a geological survey if there exists a requirement that it acts to maximise output rather than profit, with no exclusive rights to exploitation of the monopoly.

Furthermore, there are many uncertainties caused by the lack of commercially relevant and reliable management information concerning the geological survey, necessary to assess viability in the new regulatory setting. Why should potentially interested companies bid on a franchise, license, concession or even management contract? They would expect government to pay a large risk premium, negating any financial advantage to the nation.

In most regulatory reformation of their national surveys, governments have chosen to establish special agency status whereby political accountability for the performance and ownership of the information assets remains with government.

18.7 Conclusions

The paper has set out to develop an economics model concerned with efficiency in pricing and distribution of national geological survey materials. The constraints are that output be as large as possible without permanent subsidy to clients, and that government must be assured of unlimited access to the results. A significant outcome of the model is that it leads to a management framework enabling a geological survey achieve these strategic objectives.

The main conclusions may be summarised as follows:

1. Under the constraint of the three strategic objectives of Government, economics provides a conclusive argument about efficiency in the pricing and distribution of geological framework data;
2. Indirectly, economics also indicates the management framework required to achieve these strategic objectives;
3. The context for privatisation is provided by the strategic objectives together with the management framework
4. On condition that a level playing field is provided for access to products in the geological survey's natural monopoly, the geological survey may participate in the value-added competitive market in which the products of the monopoly are needed. Thus, based on the economies of scale of the monopoly, economies of scope can be realised.
5. The competitive market must meet "*what society wants*" whereas the Natural monopoly and public interest is concerned with "*what society needs in the longer term*" (Figure 18.3).
6. In addition to realising economies of scope, participation in the value added competitive market may provide the geological survey better insight into what society needs for the continued relevance of their systematic activities.

There is an on-going evolution to the perception of public interest. For example, historically, the quality of the science was a principal goal in the past for many geological surveys. Now the quality of society and the contributing role of (geo)science to such a goal is the main focus for the typical geological survey. Systematic earth resource inventories in the national context are natural monopolies, the content of which is influenced by the changes in perception of the public interest.

Geological surveys need to be aware that their activities are increasingly taking place in the context of a national geospatial data infrastructure. This in turn will facilitate the broadest possible use of the public investment in geospatial data, information and knowledge.

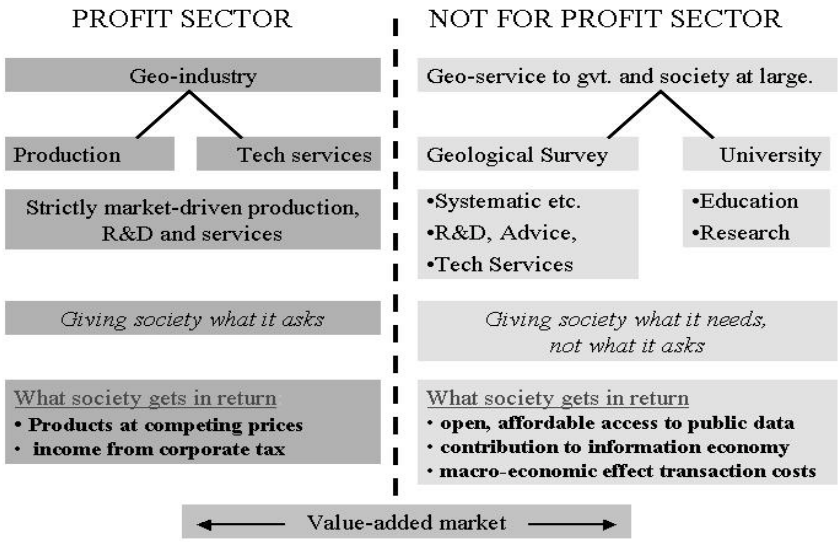

Figure 18.3. What society needs and what society asks from geoscience

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19 Access to national geoscience repositories using digital geoscience spatial models

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19.1 The Context

National geological surveys organisations (GSOs) traditionally have collected a range of geoscientific data, often based around the geological map and included in descriptive reports or memoirs. Governments commonly regard these data as an important baseline for strategic information of relevance to the socio-economic development of the nation, which is why the state funding for such organisations is almost universal. Where the national wealth is strongly focussed on resources, there is a clear relevance of geoscientific information. Where, as in many European countries, populations are less dependant on resources for their income, exploitation of resources may be seen as contrary to the public interest. Here the impact of pollution and hazard take a higher profile and understanding of the concealed structures assumes considerable importance.

The funding for GSOs is often tenuous and uncertain, even where there are demonstrable benefits from the information that is held. However, it is unusual for the information to be directly useable by the engineer, the environmental consultant or the mining geologist. The data will require processing, interpreting, and demystifying for use by non-geoscientists. To continue to be relevant and to justify their funding, GSOs must ensure that their data are relevant for specific uses, accurately classified for quality, provenance and suitability, up-to-date, and held in a repository that is accessible, user-friendly and 'intelligent'. The purpose of this paper is to describe the problem, to identify approaches that contribute to solving it, with particular emphasis on the use of geoscientific models to provide information.

19.2 The role of a Geological Survey Organisation

The traditional role of the GSO has been to capture data manually and publish hard copy maps and reports. A major revolution has accompanied the introduction of computer technology, significantly aiding the process. Currently, data are processed through computers several times, adding value at a number of stages be-

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tween capture and publication (Culshaw, *this volume*). However, it is unusual for the data to remain within a single workflow, within a single medium: it is normal for hardcopy translations to be taken and operations carried out on that hardcopy before re-entering the digital domain. This is clearly inefficient and potentially loses information.

Many GSOs hold their primary or observational data in databases, which are often islands of excellence and completeness. However, it often takes considerable effort for databases to be joined. This is because of different standards of classification, units and naming, and because of inadequate or non-standard metadata. Subsequently, the primary data may be accessed by different users for different purposes and put through a range of analyses (which may be called processing, reduction or modelling). It is very unusual for these results to be systematically stored, normally being retained in project stores. Apart from within the processing report, little information is provided about the derivation and provenance of the analyses, yet these may have involved the input of considerable expertise and knowledge. Each time such analyses are completed, without the results being stored to corporate standards, a GSO potentially loses benefit. The same, of course, applies to the final output – the map or the report. Without careful referencing and reading, it can be difficult to identify available, valuable expertise and knowledge concealed within the output.

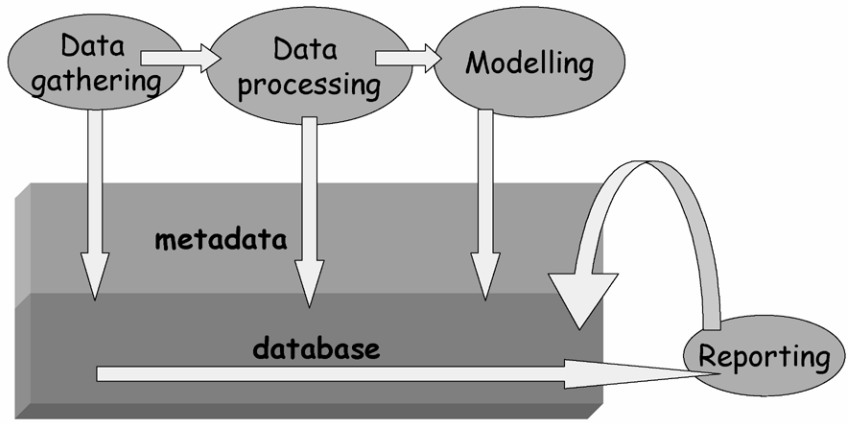

Figure 19.1. Illustrating the flow of data within GSO databases; value is added by successive processes of validation, conversion, reduction and selection

GSOs are tackling these issues and a range of solutions is being developed, based around the use of metadata and standards. Figure 19.1 illustrates the flow of data and indicates that, at each stage of analysis, new metadata are required. It suggests that access to data depends on its associated metadata.

19.3 Strategies for preservation of information

It is important to minimise the translation of data into different media as the data are processed, thereby reducing the loss of information at each stage. This can only be achieved by a careful analysis of the work-flow involved, so that the output of each process can feed directly into the next process.

Metadata, in different guises, can help to overcome some of these difficulties by providing information about the specific geoscientific data, enabling a user to identify required datasets and to establish important information about the data (such as how it was derived, its intrinsic quality and to find how it is made available).

Standards are crucial for data management. The standards adopted for data may be local or they may be international, as appropriate for particular cases. More important is adequate training of data managers and enforcement by data administrators to maintain the standards. GSOs should try to adopt standards that will ensure that their customers are provided with consistent data, using widely accepted units and nomenclature that are properly described by their metadata.

The classification of datasets must be considered: this involves both metadata and standards. Datasets may be classified by keywords (or key phrases) according to accepted standard definitions. These fall into a structured hierarchy – often known as a thesaurus – designed to make 'drill-down' procedures into the data repository both accurate and efficient. During the 'drill-down', the user should be presented at each decision point by a limited number of rational choices, but equally there must only be a limited number of decision points, to avoid frustrating the user. This requires a careful analysis of the data held and adequate training of data managers.

Another relevant aspect of classification is the use of data dictionaries or vocabulary. The GSO should maintain those with a corporate application, so that users can add new codes as required with only the necessary level of bureaucracy to ensure that quality is maintained. Similar dictionaries should be merged to eliminate duplicates. A good data dictionary should enable coding of information to be carried out to accepted standards. It will also begin to constrain the collection of data to the required attributes and standards.

One of the disciplines in experimental science is the computation of an error budget. However, in geoscience generally, such rigour has been forgotten. Users of the information that GSO's hold are beginning to ask how good are the data; they need to know the confidence limits. It is important, if the data are to retain credibility, that estimates of confidence are made and are provided alongside the data.

19.4 The Digital Geoscience Spatial Model

The Digital Geoscience Spatial Model (DGSM) is a concept that recognises that many of the activities that geoscientists carry out can be regarded as 'Modelling'. It builds on the strategies described above and extends them into multi-

dimensional modelling. The term was coined by Loudon (2001), who recognised that GSOs hold the geoscientific understanding of a country in a large variety of media and that much of the understanding was encapsulated in a visualised model. The ideas largely developed from his treatise published as a Special Issue of Computers and Geosciences (Loudon 2000).

Modelling is the attempt to encapsulate the real world in a way that can be understood and communicated to others. Spatial modelling is a means of communicating the shape and form of a multidimensional body by means of a scaled picture, often in two dimensions (as in a cross-section) or the three-dimensional block diagram. Conveying a fourth dimension is attempted by constructing a series of two- or three-dimensional pictures representing the changes in shape of a body. These models can be done by arm-waving ("The fish that got away"), by drawing on paper (either accurate scale drawings or by sketches that encapsulate the essence of a rock-body) or by representing these on the computer (as image files, or as the 3D visualisations from modelling software such as portrayed by 'Data Caves'). It should be emphasised that a high-technology solution is not essential for effectively showing the information. The important aspect is to encourage the geoscientist to capture the information in a digital form and to link it to a visualisation that can be explored.

If the information is managed in a structured way, it is possible to explore it to discover the specific requirements of the user. Figure 19.2 illustrates this in a simplistic way. The model alone, with no text, would be more or less meaningless, except to those already familiar with it. However, using a menu system to select required items, the description of the model can be displayed, the stratigraphy of the rock-mass indicated, the hydrogeological processes shown and, finally, the resources can be identified. This principle can be extended to varying levels of detail for each theme, so enabling the required detail to be presented.

The main requirements for these principles to be implemented are the means of identifying relevant models in an area, storing the models in such a way that they can be retrieved and viewed. Also required are methods of holding information about the models – both as metadata and as structured text and images – and the means of linking and drilling into the datasets. These requirements are being explored in a British Geological Survey (BGS) programme, established in 2000, based on a scoping study by Smith et al. (1999).

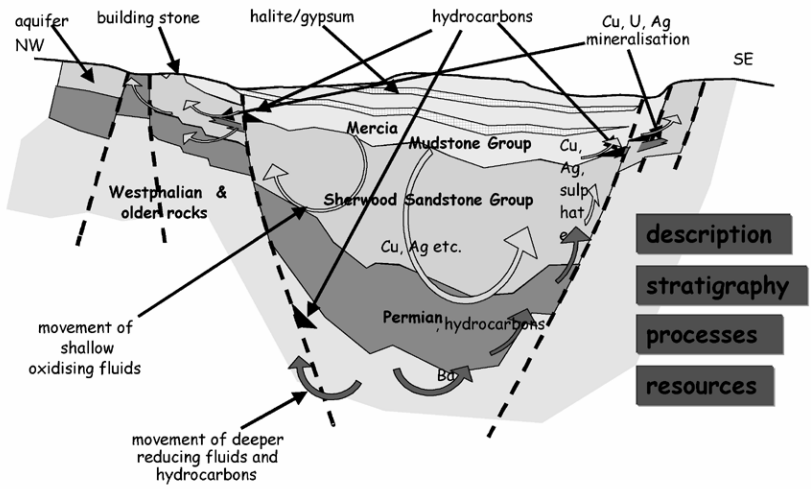

Figure 19.2. An image of a digital model, illustrating in a simplistic way that the model is a means of conveying information about the concealed geology. Generalised section across Cheshire Basin (courtesy Dr D G Jones) based on seismic and borehole data

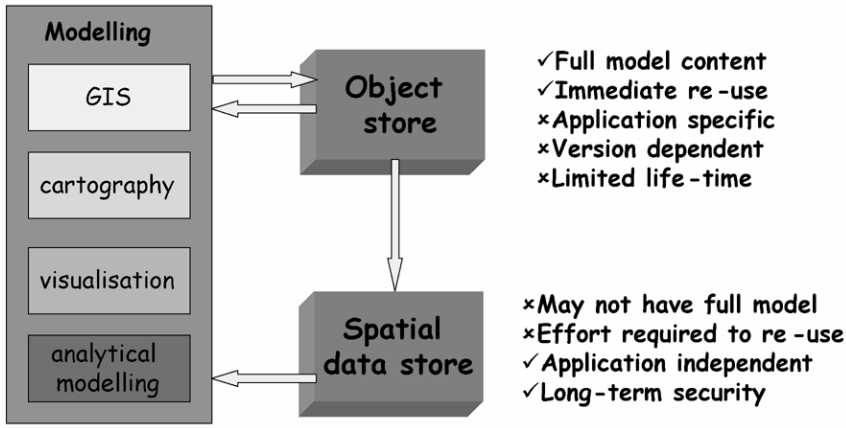

Figure 19.3. The logical structure of the data store

19.5 The requirements for a Digital Geoscience Spatial Model

The most important single requirement for a successful DGSM is that data are managed according to corporate standards. BGS has established a system called BGS-geoIDS (Baker and Giles 2000) that sets such standards for the organisation. The challenge is promulgating and policing the standards.

A means of storing models and other digital objects is required. For immediate re-use of application-specific models, BGS is developing a Geoscience Large Object Store. This holds 'Technical Metadata' on the application that produced the object, so that it may be re-used in the same application. The models are associated with 'Discovery Metadata' and key-phrase classification to aid identification, and with 'Inference Metadata' that describes how the object was derived from the input data. The store will hold any object relevant to the description of the geoscience, such as images, spreadsheets and so on (Figure 19.3).

In the longer term, the spatial model must be shared between applications. This will require a generalised data structure that will allow the geometry and interrelationships between shapes to be stored. This will be populated by the output of a specific application, and will provide data that can be utilised by other modelling applications.

Structured metadata (Figure 19.4) will ensure that it is possible to identify the source of data used to build the model – this has been called Data Discovery Metadata. These datasets will pass though a number of processes in the course of building the model. Information on these processes needs to be captured and stored, so that future users are aware of them; this information has been called Inference Metadata. This links to the model itself, which will require Model Discovery Metadata. Each of these types will conform to, or extend, existing standards.

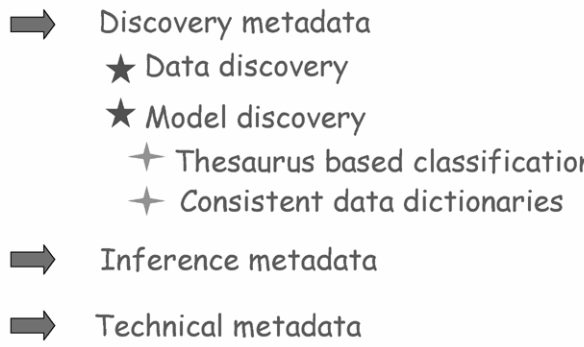

Figure 19.4. The importance of metadata

Each object will also be classified with Key Phrases, as described earlier. Attributes of models and other entities will use data dictionaries to constrain the data entry to agreed ranges of codes or values. Standard thesauri and dictionaries are being adopted and adapted.

To address the issue of quality, a documented 'Best Practice' will be required for each type of model and it is expected that this will be followed during modelling work. Exceptions to this standard approach will be recorded. It is important to understand and record how well the model is believed to represent the real world as a result of the complexity of the real world and the distribution of relevant data; to evaluate the quality of the data, and the interpretation (Figure 19.5).

In order to describe the details of geoscientific knowledge, a means of marking text with 'tags' with geoscientific significance required. The eXtensible Mark-up Language (XML) is being investigated to develop a Geoscience ML. This will encapsulate the standards of data dictionaries in selecting sections of text that cover the relevant topics. This strategy has been utilised by Duffy (2000) in the Digital Report Generating System. It is being extended to a wide range of geoscience data types. This can be applied to existing digital reports but will also have applications in writing new text, which might be stored as 'micro-documents'. These micro-documents might be seen as attributes of the model and will contribute to a thematic report on the model.

The preceding requirements define the constituent elements that will make up the DGSM. To make it useful to users of the information, access will be developed over the Internet. It will be critical for users to be able to view the models in an attractive, flexible way over the Web. Virtual Reality Modelling Language (VRML) may provide for that. Alternatively, Java-based viewers might deliver better performance and flexibility. Web-based map-services, coupled with query-driven menu systems should enable the flexible access to be delivered (see van Wees et al., *this volume*).

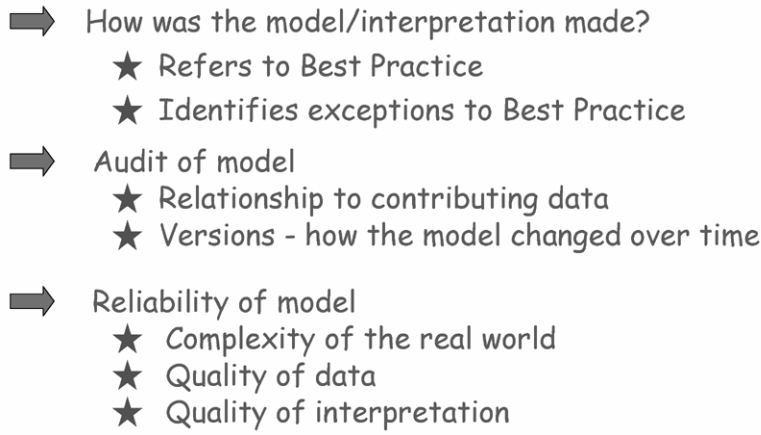
How was the model/interpretation made?
Refers to Best Practice
Identifies exceptions to Best Practice
Audit of model
Relationship to contributing data
Versions - how the model changed over time
Reliability of model
Complexity of the real world
Quality of data
Quality of interpretation

Figure 19.5. The quality issues

19.6 Conclusions

The DGSM brings together a number of modern technologies into a framework for what is believed to be a practical way to deliver the accumulated understanding of the geoscience for an area. Little mention has been made in this paper about the building of these models. That will require a corporate strategy to alter the prevailing attitude from the publication of paper maps and books into building systematic models of agreed themes. It will take a long-term view to develop systematic and coherent coverage. There is no single model that will accommodate all the understanding of the rock-mass: different parameters will be mapped at dif-

ferent resolutions for different purposes. The benefit will come when these models can all be compared within a single digital environment, knowing that they are defined in a consistent manner. Then they can be compared, refined or revised in the light of each, which will lead to an appreciation of the limitations of each thematic model and where it might contribute to others. As a long-term view for the objectives of GSOs, this must be a worthwhile objective.

Acknowledgements

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van Wees J-D, Versseput R, Allard R, Simmelink E, Pagnier H, Ritsema I, Meijers P (2003) Dissemination and visualisation of earth system models for the Dutch subsurface *[Chapter 20, this volume]*

20 Dissemination and visualisation of earth system models for the Dutch subsurface

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20.1 The Context

For more than a century, geological surveys have gathered a great amount of subsurface data. Within the last decade, major technological advancements have revolutionised geoscience interpretations. Multidisciplinary teams can produce increasingly complex 3D models of the subsurface that incorporate data and interpretation uncertainties. These advancements have provided high added value to exploration and production business processes, but the required technologies to build and effectively share these 3D models and their original data are very expensive. This is mainly due to the high costs of software licenses, often exceeding 30k Euro per license. This severely limits the access to and visualisation of key data and associated models in 3-dimensions by a broad audience.

This constraint is especially troublesome to national geological surveys because they are increasingly facing demands to provide their geoscience information and knowledge to society in forms that are easily understood and at low cost. Existing commercially-developed products are too complex and too expensive to meet such needs. Many are designed for use on relatively expensive UNIX-based computer workstations. Yet in the last few years, relatively cheap personal computing hardware, software, and operating systems have become sufficiently powerful to undertake many of these 3D model developments and visualisations (see for instance van Wees & Kok, 1999). When these are coupled with Internet-based dissemination tools, it is possible to create a cost-effective solution that can support the widespread use and dissemination of 3D geoscience information.

Society requires low-cost and easy-to-use methods for disseminating and visualising 3D geoscience data. The initial challenge facing the Netherlands Institute of Applied Geoscience TNO – National Geological Survey (TNO-NITG) was a requirement to disseminate to the public at low-cost the data and volumetric models of the deep subsurface of the Netherlands.

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20.2 Digital database of the Dutch subsurface

TNO-NITG is charged with archiving, ensuring the quality of and disseminating information on the subsurface in the Netherlands. To that end, TNO-NITG started developing an information system in 1997 that was named DINO, a Dutch acronym for Data and Information of the Dutch Subsurface. Ultimately DINO will be a storehouse for all the geodata and information that TNO-NITG manages. The institute checks the quality and accuracy of that information and makes it available to anyone who needs it.

Within DINO, TNO-NITG has already created a digital database that corresponds to the 1:250,000 scale geological maps of the Netherlands that were formerly published as map sheets. The database contains depth interpretation of key horizons based on interpretations of a large number of 2D and 3D seismic surveys and hundreds of wells. Subcrop patterns and fault lines are included as required for every horizon, and are stored as digital line files, while the horizons are defined by digital grids at 250 m resolution. Stacking the horizon grids and using subcrop information allows construction of volumetrically consistent layered models.

20.3 Dissemination and visualisation system

In 1999 TNO-NITG conducted a market-research study to get an overview of the available 3D modelling and visualisation tools for the geosciences (van Wees *et al.*, 1999). This research concluded that no available software allowed the 3D visualisation of geoscientific data on a PC by the general public. Available tools were simply too expensive, too discipline specific or lacked the features essential for real understanding.

Therefore TNO-NITG decided to establish a dissemination and visualisation system that consists of three components:

- HTML navigator web page (Server-Client)
- Java Servlet (Server)
- 3D Java Viewer (Client)

20.3.1 The Web-based dissemination component

The HTML navigator web page can be accessed from any computer with an Internet connection through the TNO-NITG website: http://dinoloket.nitg.tno.nl. This web page, which has been developed using ArcIMS from ESRI, allows the user to graphically define any desired study area either by selecting a map sheet, a province, or a rectangle (Figure 20.1).

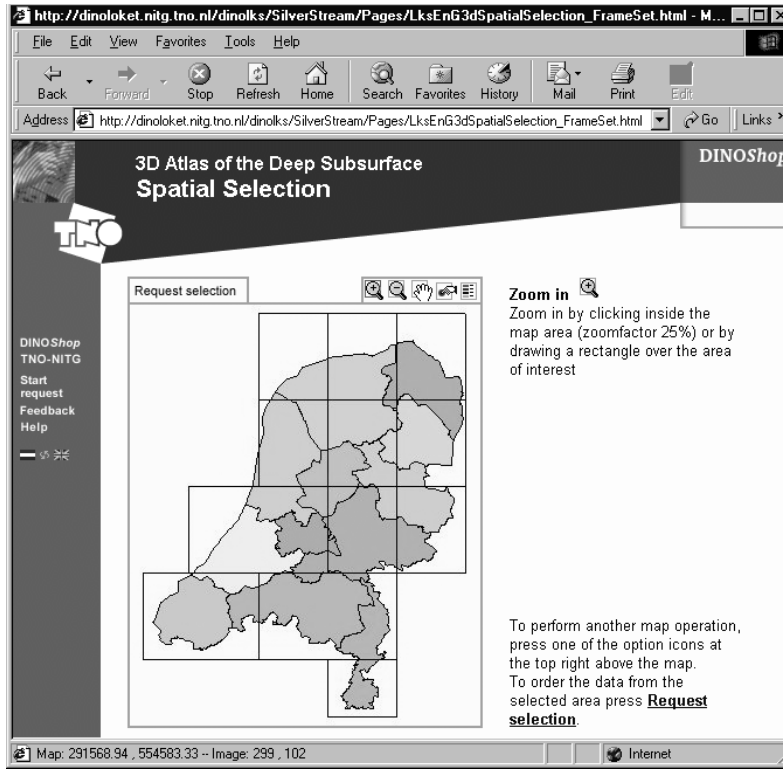
http://dinoloket.nitg.tno.nl/dinolks/SilverStream/Pages/LksEnG3dSpatialSelection_FrameSet.html - M...
File Edit View Favorites Tools Help
Back Forward Stop Refresh Home Search Favorites History Mail Print Edit
Address http://dinoloket.nitg.tno.nl/dinolks/SilverStream/Pages/LksEnG3dSpatialSelection_FrameSet.html
Go Links
3D Atlas of the Deep Subsurface
Spatial Selection
DINOShop
TNO
DINOShop
TNO-NITG
Start request
Feedback
Help
Request selection
Zoom in
Zoom in by clicking inside the map area (zoomfactor 25%) or by drawing a rectangle over the area of interest
To perform another map operation, press one of the option icons at the top right above the map.
To order the data from the selected area press Request selection.
Map: 291568.94 , 554583.33 -- Image: 299 , 102
Internet

Figure 20.1. Accessible HTML navigation web page for selection of subsurface data

Subsequently, the actual selection is performed by the TNO-developed Java servlet, which takes care of sampling the data, packaging the data in a Zip-file and sending it through E-mail. A single selection down from the servlet menu suffices to create a complete model of the chosen area (Figure 20.2). This simple access to a complete model contrasts with the rather elaborate ways required to load models into other tools. Currently, the DINO deep subsurface data are stored as flat files. Future plans call for this dissemination method to be expanded and used to access a central database containing all the data and models used by TNO-NITG.

20.3.2 The Client-based 3D visualiser

On the client-side, these data sets can be visualised in 3D with a Viewer called "Geo3DJViewer" developed by TNO-NITG. This viewer was developed in Java by using the Java 3D extension and using a 3D geoscience library from INT Incorporated, located in Houston, Texas (http://www.int.com). In May 2001 TNO-NITG released the first public version of this Geo3DJViewer (van Wees *et al.*, 2001). The viewer can be used to visualise the Dutch subsurface data from the

TNO-NITG DINO database and is freely downloadable from the website: http://dinoloket.nitg.tno.nl/.

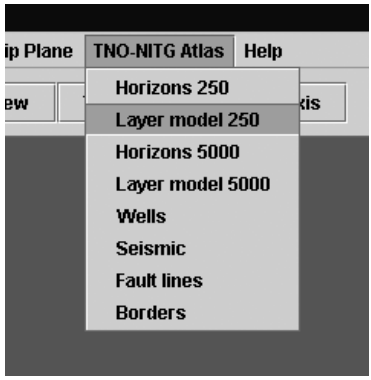

Figure 20.2. Menu items to load models

The Java platform was chosen because:

- It is platform independent, and all major platforms are supported;
- It is a modern object-oriented language that speeds up the development in comparison with a language like C++;
- A high level object oriented 3D library is available as a standard extension;
- There are no license costs.

Some have argued that Java is too slow to become a suitable platform for creating high-performance applications. Although this may have been true in the past, modern Java virtual machines use dynamic optimisation and compiler techniques that make Java competitive with C++ and FORTRAN applications (Bull *et al.*, 2001). The SciMark 2.0 benchmark provides additional clear evidence of the improvement of the Java platform in recent years (Pozo and Miller, 2001).

Experience to date with the Geo3DJViewer indicates that memory usage is the most critical factor. Currently all surfaces are defined by regularly spaced grids. On a PC with 128 Mb running Windows NT4.0 it is possible to visualise models consisting of about 10 layers and more than 500,000 nodes. Since new PCs tend to have 256 Mb memory as standard, such performance appears to be quite acceptable. Moreover, it is expected that in the near future it will be possible to reduce the memory footprint significantly.

20.4 Capabilities of the Geo3DJViewer

The Geo3DJViewer has powerful capabilities: it can change attributes of data, including colour contouring of both grid data and point attributes, and has options to drape georeferenced bitmaps. It allows the user to query and select data in a similar fashion to features found in 2D GIS systems. One of its most powerful features is the capability to create arbitrary cross sections through the layered models.

The viewer resolution can be tuned to the capabilities of the client-computer to gain optimum performance. Common 3D navigation tools are available such as shifting, zooming and rotation. These provide the user with the ability to dynamically view the model from any desired viewpoint. The vertical exaggeration (Z-scale) can be changed using a slider. An object browser organised in the form of an object tree allows the user to add or remove objects within the view, and to change the appearance of the objects (Figure 20.3).

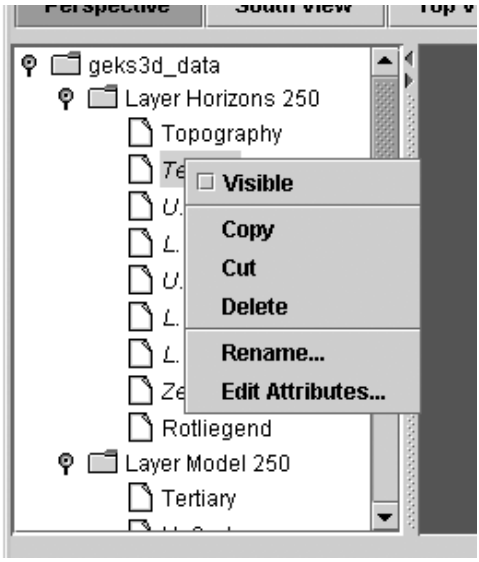

Figure 20.3. Object browser

The Geo3DJViewer visualises a series of stacked layers defined by a series of surfaces S_0, S_1 ..... S_n. where each pair (S_i, S_{i+1}) of consecutive surfaces defines a layer L such that the bottom of L is S_i and the top of L is S_{i+1}. Such a series of stacked layers can be visualised by generating and rendering its hull H. An example is given in Figure 20.4.

It is possible that layers vanish locally. In rendering the hull H it may thus be necessary to colour the top or bottom surfaces locally according to the layer that is present. In the Geo3DJViewer this is achieved by draping the top and bottom surfaces with textures. By taking finely-meshed textures, relatively smooth contacts are achieved. Figure 20.5 shows an example of the result of this technique. The

bitmap textures can equally well be used for displaying other information, such as plotting roads or river locations on the top surface of the layer model.

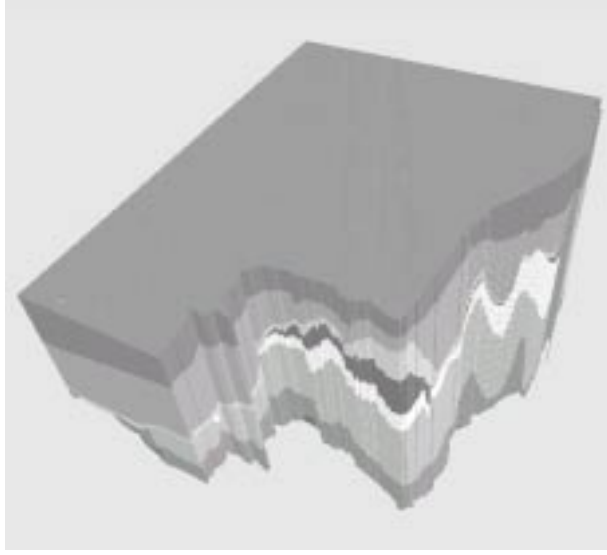

Figure 20.4. Example of stacked layers

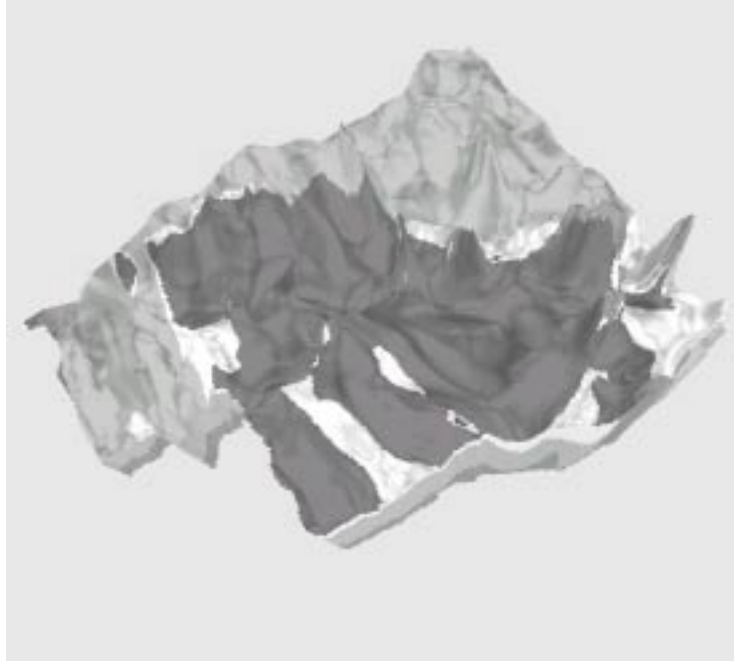

Figure 20.5. Locally vanishing layers

Planes can be added to the scene to clip a model and/or add cross sections. Figure 20.6 shows the model displayed previously in Figure 20.4, clipped by a horizontal plane (top) and a vertical plane (front).

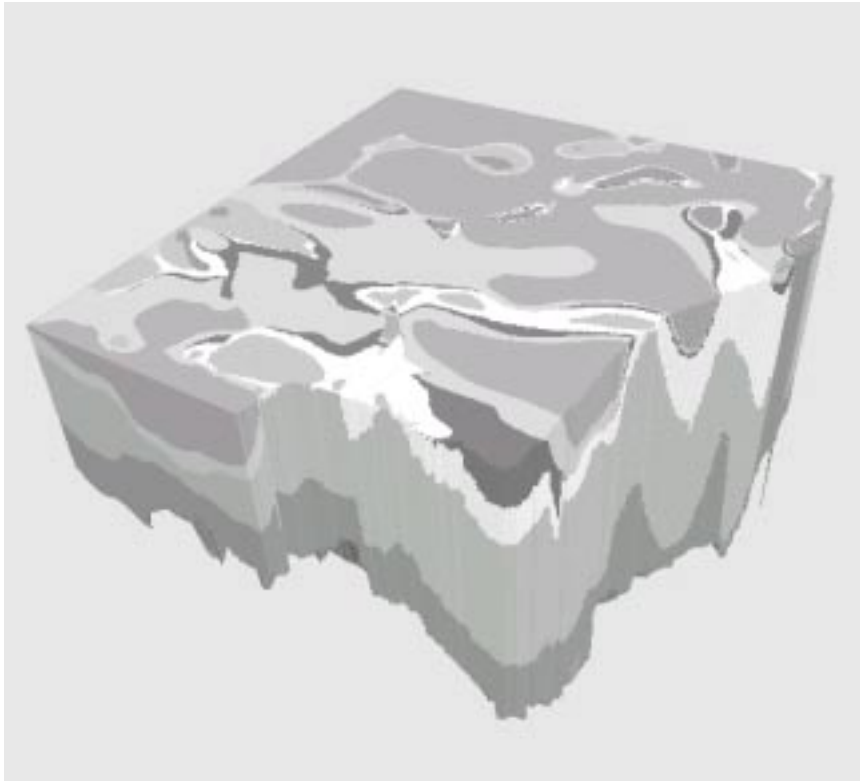

Figure 20.6. Layer model clipped by two planes

The volumetric imaging results when textures are attached to these clip planes. Such planes can be displayed without the surfaces to create ordinary cross sections. Figure 20.7 shows the same model, but only displays the two vertical cross sections and the bottom of the model. Up to six individual clip planes can be defined simultaneously and these planes can be shifted and rotated independently. This allows the user to slice interactively through a model.

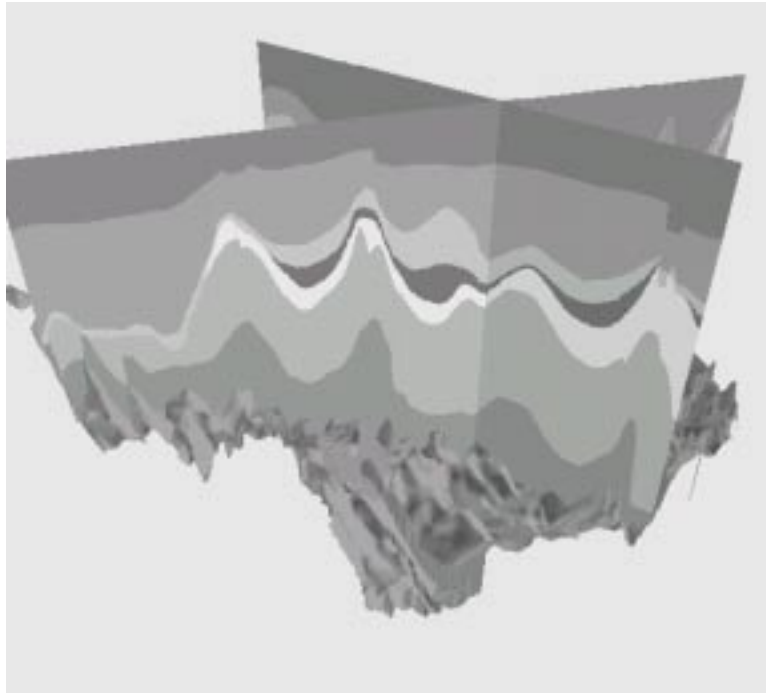

Figure 20.7. Two vertical cross sections

20.5 Future development of the viewer

Continued development of the Geo3DJViewer will address the following issues:

- ***Floating bodies***. These are volumes that float inside a layer belonging to a stacked sequence
- ***3D property models***. Models described for instance by voxel sets (3 dimensional grids)
- ***Triangulated surfaces***. Ability to display volumes described by surfaces
- ***Dynamic models***. Time dependent 3D models
- ***User defined models***. Users can define their own models. However these models cannot yet be stored; eventually XML will facilitate this
- ***Seismic data.*** Tend to be large; enhanced viewer performance required
- ***Enhanced performance***. Hope to reduce memory footprint significantly
- ***Visualisation of uncertainty***

- ***Efficient database links.*** Required to support future TNO-NITG goals for storing all geo- referenced data within the central database.

20.6 Added value for geoscience interpretation

The dissemination and 3D visualisation system caters for a clearly emerging need for improved access to digital subsurface data, especially subsurface 3D models, stored and built by geological surveys. These tools provide a way of proliferating in-depth knowledge of the subsurface quickly by anyone working with earth system data, both specialists and others, including politicians, government officials, technicians and the general public.

This type of viewer may be used in areas as diverse as geological surveys, mining, groundwater and oil exploration and production, civil engineering, and environmental studies. By providing low-cost access to earth system databases, these tools are potentially of interest to drilling contractors, emergency services agencies, engineering firms, utility companies, and local government authorities.

20.7 Conclusions

The Java platform appears to be well suited for developing high-performance 3D visualisation tools. Modern PCs can be used for visualising complicated 3D geological structures and models. 3D tools offer people working with subsurface data insights that are otherwise hard to obtain. It is expected that the use of 3D visualisation tools will become widespread in the geoscientific community.

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Part E Property Prediction

Investigations in the shallow subsurface generally require much higher feature resolution, more precise property matching, and the ability to differentiate conditions in a noisy environment, when compared with the investigations conducted for petroleum or mineral exploration. Engineering geophysics has evolved to provide high-resolution imaging to depths of a few tens of metres, offering the ability to correlate sparsely-spaced in situ tests and samples from which laboratory determinations have been made. Traditional sampling methods are being further supplemented by innovative penetrometer techniques, particularly for soft ground, and by directional drilling and coring methods.

The very shallow urban underground environment, where many infrastructure and utilities elements are located, presents the most difficult characterisation problems. Characterising slightly deeper portions of the shallow subsurface is important for groundwater resource evaluations, environmental contamination assessments, and for some infrastructure applications such as underground fluid storage and deeply buried facilities.

The efficient management of data – including metadata – is of great importance. Updating/logging of old data records is a time consuming but very useful task, allowing easy future use of past recorded data in modern models. Nevertheless uncertainties exist in both recorded data and that predicted in models. What is the best way to present this? Validation of both data and models is required for full confidence in any model.

It is becoming increasingly clear that achieving a more complete understanding of the Earth's geological systems will require ever increasing degrees of integration of data, insights, and the perspectives derived from many subdisciplines. The considerable research efforts that have been devoted to subsurface characterisation over the past decade offer a means for integrating spatially referenced data, and provide important visualisation and interpretation tools. The current systems are based on fundamental data models developed in the 1970's and 1980's - an era with a very different computer technology from that available today. The changes in computer technology, and the evolution of our concepts of information management, dictate a new evaluation of these fundamentals. Yet an important question remains: how can the use of these subsurface characterisation methods be made easier and more productive?

Appropriate procedures and software are required to allow the knowledge and experience of geologists to be imparted during modelling and data presentation. This should allow the incorporation of 'expert knowledge' into geoscience models to be made as easy as possible. Such capabilities are especially important when defining and predicting properties of earth materials.

Ideally it should be possible to predict the lithology and properties of rocks in 3D/4D space. This remains a huge challenge, and required the development of appropriate correct tools and high quality data.

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21 Total Geological History: a web-based modelling approach to the anticipation, observation and understanding of site conditions

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21.1 The Context

The concern is with the effective use of computers to assist site investigation where subsurface conditions must be predicted. It deals with qualitative rather than quantitative aspects of investigation, utilising the numerous case histories which suggest that failure to anticipate leads to failure to observe and understand. Following Fookes et al. (2000) it is argued that the geological model is the key to predicting subsurface conditions.

Technology offers investigators help in developing the model for their site. However, the approach advocated here is reflective rather than deterministic. This leads towards ideas contained in the knowledge management literature rather than expert systems. It also raises communication issues.

The result is a web-based approach designed to help users identify the geological and geomorphological processes that have produced the present conditions. The identification of these processes generate a list of subsurface conditions that are most likely to exist and which the subsequent detailed investigation should seek to locate.

The aim is to guide the cross-disciplinary research agenda for geological modelling and computer science. The issues raised and the language used are specific to workers in these fields. In this context, 'technology' refers to information and communications technology; 'web-based' is used as an abbreviation for those technologies which are generally associated with the world wide web, even though they may be used on a stand-alone computer.

21.2 Total Geological History

The mechanics used by geotechnical engineers are largely based on the concept of an isotropic homogeneous continuum. In practice geological materials are often ir-

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regularly arranged and highly variable. This variability gives rise to uncertainty and presents a serious risk to building and civil engineering construction.

Ground conditions at any site are a product of its total geological and geomorphological history (Fookes 1997). To understand this history, it is necessary to develop a site specific geological model based on consideration of the regional and local geological and geomorphological conditions (Fookes et al., 2001). Development of the model begins during the initial desk study. How far the model can be developed at this stage depends on what published information and local knowledge is available. Even when detailed maps are available, interpretation is dependent on a fundamental understanding of the regional and local geology. The model may be refined throughout the investigation even though much of the geology will be known in the early stages of the investigation. As Figure 21.1 indicates, the main geotechnical data acquisition will take place in the later phases of the investigation and should be informed by the geological model.

21.3 Initial models

The model approach uses three sets of initial models first presented by Fookes et al. (2000):

- **Ten global scale tectonic models**. These cover large areas (typically many tens to hundreds of kilometres) and set the scene for anticipating the regional structure and rocks of the area.
- **Seventeen local (or site scale) geological models** (typically covering kilometres to tens of kilometres across). These relate to the rock forming environments and to tectonic and diagenetic changes
- **Eight local (or site scale) geomorphological models.** These relate to current and recent past climates (i.e. Tertiary and Quaternary Ages).

21.4 Case history: Emerson Green

A simple example illustrates both the importance of understanding the geology and the roll of the initial models. A 50 m section of cut slope for the A4174 Avon Ring Road at Emerson Green, north-east of Bristol (UK) failed in February 1999, about 8 years after construction (Figure 21.2).

The old UK 6 inches to 1 mile geological survey map ST67NE (i.e. 1:10,560 scale) shows a complex pattern of outcrops in this area from the Upper Coal Measures (near the top of the Carboniferous). These were extensively folded and faulted during the Variscan (Armorican) tectonic disturbances. The ground above the slip plane in a highly weathered silty MUDSTONE dipping at 20° to the east, parallel to the slip surface shown in Figure 21.2. Below the slip plane and outcropping to the north is sandstone. Both rock types are described on the site inves-

tigation report dated September 1989. The mudstone is described as "very stiff brown silty CLAY with many sub-angular mudstone lithorelicts to coarse gravel size". The angle of friction for the more weathered material above was said to be 22° with a cohesion intercept of 34 kPa. The cohesion intercept suggests this was a peak strength rather than a critical state strength, which did not fit well with the highly fractured nature of the mudstone. The designers clearly relied on this because the slopes were constructed at 26°. The original site investigation report provided no indication that a model of the geology had informed the geotechnical data acquisition.

21.4.1 Developing a site specific model for Emerson Green

The approach to developing a site specific model for Emerson Green began with the published set of initial geological and geomorphological models (see Section 2.1). After consideration of all the models, one or more of these models will be identified to represent the particular site.

The geological model for open folds and joints shown in Figure 21.3 (from Fookes et al., 2001, Figure 3.12) anticipates the failure mechanism where weak mudstone overlies sandstone with a fold axis nearly parallel to the road. The intra-formational shear (bed over bed slip) has reduced the shear strength below the peak value and possibly as low as its residual strength. There is a clearly defined shear surface in the mudstone just above the sandstone. Tests on clay from this band showed the residual angle of friction to be about 17°. The slip did not happen at the time the road was constructed because the excavation reduced the total stress and hence set up negative pore water pressure. This negative pore water pressure dissipated over time, leading to failure several years after construction.

21.5 Geological Environment Matrix (GEM)

The conceptual precursor for the Total Geological History model was the Geological Environment Matrix (GEM) presented by Fookes (1997). Understanding GEM helps towards understanding the initial models. Both GEM and the initial models are based on the premise that the geology of a particular location is the sum of its history including:

- Formation and alteration, including faulting and folding
- Modification by geological activities including igneous intrusion and metamorphism
- Surface and near surface influences including marine and glacial processes.

GEM presents this as a matrix, One axis is divided into four principal rock-forming environments; each is subdivided into sub-environments. The other axis

is divided into five rock modifying environments, each again subdivided. The two axes are presented as columns in Table 21.1 for reasons of space.

Fookes suggests further subdivisions to create sub-sub-environments (e.g. Bb1, reverse faults, Bb2 normal faults). For each sub-sub-environment there should be a table detailing both the geological and the engineering features plus associated key words, appropriate site investigation procedures and cross-references to other sub-sub-environments which may be associated with this one.

These tables were seen as an *aide mémoire* to assist experienced geologists develop site-specific models of the total geology. The risk that these tables may become too detailed and cumbersome is acknowledged. The geological environment matrix is important because it led to the development of the initial Total geology models.

The initial models provide a better way to communicate the information contained in GEM. Figure 21.3 illustrates one of the initial geological models, the full set can be found at URL: http://www.uwe.ac.uk/geocal/totalgeolgy. The models work because they represent real systems in their entirety; engineers and geologists can identify with them from direct experience.

21.5.1 Digital data

Fookes (1997, First Glossop Lecture, page 398) suggested that GEM was likely to benefit from computerisation and mentioned database software and keyword searches. When the Total Geology models were created, it was clear that they were suited to presentation in a computer based system. The computerised version discussed here uses world web technologies: DHTML and JavaScript. Currently it does not depend on web server technologies (e.g. CGI scripts) and can be run from a CD on a standalone computer. The reasons for this approach are presented below. What follows applies specifically to the process of developing a site specific geological model.

Attention is drawn to the words of Evert Hoek (1999, Second Glossop Lecture): "The three-dimensional block drawings and sections included in the written version of the first Glossop Lecture, prepared by Mr G Pettifer, are miniature masterpieces of geological art. If only such drawings were available on all construction sites. ... Help for artistically challenged geologists is on the way in the form of computer generated three-dimensional models."

21.5.2 Knowledge based systems

Standard texts on Artificial Intelligence (AI) contain examples of games such as chess and tic-tac-toe, but not football. Klein and Methlie (1995) describe chess and tic-tac-toe as *formal systems*. They are characterised by three essential features:

- They are token manipulation game

- They are digital in the sense that a token is either in a square or not
- There are a finite number of legal moves.

Such games can be solved by effective search procedures because the problem is well structured and the domain knowledge is limited and easily available. These procedures do not work for unstructured real world problems, such as the design of a bridge, *where there is no single correct answer.*

Predicting subsurface conditions is a comparatively well structured problem. The site defines the problem boundaries and the domain knowledge of engineering geology changes relatively slowly. Several systems have been developed (e.g. Toll, 1995). They are characterised by the following limitations:

- The output is deterministic (e.g. number and location of exploration points, methods of sampling, and types of in situ tests; Oliphant et al., 1966)
- The input required to describe the site exceeds the generated output
- Interpretation of subsurface conditions is characterised by straight lines between data points
- The total domain knowledge contained within each system is small compared with the domain knowledge in a single text book.

The deterministic nature of such systems gives rise to the danger that users may relinquish responsibility to the machine and the output will not be rigorously checked. However, this danger should be balanced against the need to process the ever increasing volume of information available.

21.5.3 Data base systems

Knowledge based systems sit at one end of a technological spectrum, the other end being a database containing all available relevant information. There are two problems with the database: (a) knowing what you are looking for and (b) knowing how to find it.

Figure 21.4 uses a 2 x 2 matrix to divided questions into four types. It is presented here to highlight the problem of knowing what you are looking for. The top row contains those questions we are aware of while the bottom row relates to questions we have not thought about. To use a database you must first think of a question. Expert systems attempt to prompt users to ask questions they may not have thought about. Of course, whether you think of the question or not, you may already know the answer.

21.6 A middle course

Davison (1998) explored a middle course between knowledge-based systems and databases. Such systems invite the user to provide project specific data, which is used to test the relevance of information held by the system. There are three outcomes to such a test:

- some information is clearly irrelevant and should not be displayed
- some information is clearly relevant and should be displayed
- insufficient data has been supplied to determine the relevance.

In the third case it may be appropriate to provide additional guidance to help the user determine the relevance.

The Web provides a convenient vehicle for such a system. The key elements are:

- A well structured information system
- A collapsible menu which exposes details as they are required
- Form elements to enable users to enter site specific information
- Rules which determine what to expose and what to hide.

The Geological Environment Matrix provided the initial information structure in this case. The Total Geology initial geological and geomorphological models provide the user interface.

21.6.1 Codifying knowledge

Figure 21.5 highlights knowledge states that may be taken for granted when seeking to develop computer systems to support site investigation. Fookes (1997) takes the total geological model approach to the third, externalised expression, stage. GEM applies a standardised scheme to this, so beginning the process of codification. The Total Geology initial models presented by Fookes et al. (2000) take codification one stage further. The computerised version described here is a first attempt at digital representation; future evolution and refinement is expected.

21.6.2 The role of case histories

The knowledge management literature has things to say about the role of story telling. Shum (2000) argues that the significance of stories, in a business context, lies not in their ability to preserve 'true accounts' of what happened in the past, but in their use as a vehicle by which an organisation preserves its collective memory and reasons about its current situation. We use case histories to preserve our collective memory and demonstrate the relevance of rules and procedure that

have been distilled from experience. Fookes et al. (2000) provided 31 case histories linked to their models. These case histories are included in the computerised version and cross-referenced to the models.

21.6.3 Navigation

Navigation is important because the models are cross-referenced and linked to case studies. As the Geological Environment Matrix suggests, keywords will become increasingly important as the system develops. Web technology has something to offer in terms of hypertext links and text searches, but the argument is not one sided. The thumb is a remarkably useful device for flicking backwards and forwards between pages; and it is relatively easy to remove the staples from a document and view several pages at once. Few have the means to use several computer screens at once.

21.6.4 Communication issues

Communication issues may make or break a World Wide Web application. First consider screen resolution because there is a wish to display at least three components simultaneously (Figure 21.6). The first component is an annotated diagram. Simple conversion to one of the web graphic file formats makes the annotations unreadable (to overcome this, the annotations were removed from the diagrams and superimposed using the positioning properties in HTML4). The second component is the commentary, which is associated with each model, and the third component is a navigational aid. Although some browsers have a 'full screen' option, normally about 16% of the screen area is devoted to browser controls. White space is necessary to enhance readability but the way it is measured varies. The reader is invited to estimate the proportion of the screen layout in Figure 21.6 devoted to prime content. The design involves a judgement about what constitutes prime content. For comparison, Nielsen (2000) presents a number of typical commercial web pages in which the prime content occupies between 14 % and 20% of the display.

Writing for the World Wide Web requires a different style from that used for academic papers. Reading is 25% slower from a computer screen (Nielsen, 2000) and few enjoy reading long passages on-line. The result is a different reading style. Readers scan information and tend to skip text that extends beyond a single screen. Nielsen and others recommend the inverse pyramid style of writing (conclusion first), simple paragraph and sentence styles, sub-heading and bullet points where appropriate.

Despite such difficulties, an estimated 20 million people in the UK spend on average of 5hr 10min per month surfing the web (http://209.249.142.57/uk/web/NRpublicreports.usagemonthly). Few of these 20 million are interested in the predictions of subsurface conditions. However, the Web offers a means or reaching a wider audience. Where the Web is used for technical material, a common motive is the transfer of printing costs from provider

to recipient; this is especially true of product support information. In other cases the Web is used to reduce delivery times and enable frequent updates.

21.7 A solution

The objectives of a digitally-based Total Geological History are:

1. to increase awareness of the need for a cognitive model of the total geological environment before the detailed investigation begins,
2. to provide a framework to help site investigation develop the model for a particular site.

These objectives dictate three target groups:

1. students
2. practising site investigation practitioners
3. project sponsors and managers

The primary design objectives are to:

1. explain the significance of the total geological environment
2. assist users identify which sub-environments apply to a particular site
3. help users develop a list of features anticipated by the sub-environments
4. clarify the significance of the anticipated features using case histories
5. provide appropriate background information
6. tread a middle course between prescriptive guidance (as some knowledge-based systems) and totally open information system
7. provide maximum accessibility

21.7.1 Interface design

The first objective suggests a World Wide Web approach. Two other factors support this decision. The first factor is the reduction in the interface development effort; this frequently exceeds 50% of the workload for traditional software. The second factor, also related to the user interface, is more important but less immediately obvious. It relates to the sixth design objective.

In the past, most software was *procedural* and characterised by flow charts. A flow chart has a start point, one or more end points and a number of decision points which determine which path the user takes. Web browsers are *event driven*. The software waits passively for the user to press a key or click a mouse button, each event triggers a related action. The freedom that is provided by the event driven web browser interface counterbalances the system designers' natural tendency to produce a prescriptive system.

Figure 21.7 shows two commercial web-based information systems targeted at professional software developers. These are noticeably different to the on-line help associated with software aimed at a wider market. These examples have been

presented here to draw attention to some aspects of the 'Total Geology' screen layout shown in Figure 21.6.

The first common feature is a hierarchical menu that communicates the structure of the knowledge base and aids browsing. In all three cases, the menu collapses to show only the section (chapter) heading and opens to reveal the sub sections. The structure is important because it help users to discover answers to questions they had not thought to ask (Figure 21.5: unasked question). Associated with the menu (contents) is an index and search facility. An initial search through the commentaries in the total geology models found 1004 words. An initial cull reduced this to 703 keywords; the current search facility is based on these words. Work continues to refine this list and provide links to the case histories.

The second common feature in Figure 21.7 is a plain uncluttered appearance. This contrasts with the common use of textured backgrounds and bold colours to appeal to mass audiences. The 'Total Geology' use of a textured background is under review.

21.7.2 Content

The prototype version of the computer-based system was a simple restructuring of Fookes et al. (2000). The current version separates the models (part 1) from the background information (part 2). A separate introduction attempts to explain the significance of the total geological environment.

The models are divided into three groups with the global tectonic models providing the setting for the other two groups of models. The site scale geomorphological and geological models have annotations and key descriptions to form the basis for the check lists, since it is these models which provide the initial basic conceptual picture of the local potential conditions.

Figure 21.8 shows some of the check boxes used to select particular models and generate the output. At this stage of development, the output is simply the commentary associated with the selected models.

Figure 21.9 shows the case history output for the two models selected in Figure 21.8. While Figure 21.8 uses a screen shot to show graphical elements, Figure 21.9 was produced by copying and pasting text; a standard simple procedure that enables users to reformat the output to suit their purpose.

21.8 Summary

Site investigation needs to develop a site-specific conceptual model of the ground before the detailed investigation begins. The model helps anticipate the ground conditions and reduces the risk of investigators failing to observe and understand:

1. The geological environment matrix provides a framework for building the site-specific conceptual model. The sub-environments with this matrix have been developed into a set of global and site scale models, in providing the starting point for a site-specific model.

2. The approach advocated here is reflective rather than deterministic. It also seeks to prompt the user to challenge assumptions and provides a check list to ensure all realistic possibilities are considered.
3. World Wide Web technologies offer a middle course between 'procedural' prescriptive systems on the one hand and open 'databases' on the other. Such a middle course raises questions which may have been overlooked; at the same time it limits the danger of excessive reliance on the computer software.

The 'Total Geology' web-site is being developed with many presentational factors in mind. A paper-based approach has much to commend it, compared with computer screens, and printout facilities are being designed into the system.

The current system continues to be developed to add new features (e.g. index and search facilities) and to restructure the existing content to improve navigation and make it easier to read on a computer screen.

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See also: Ten Mistakes in Web Design http://www.useit.com/alertbox/9605.html

See also: How Users Read on the Web http://www.useit.com/alertbox/9710a.html

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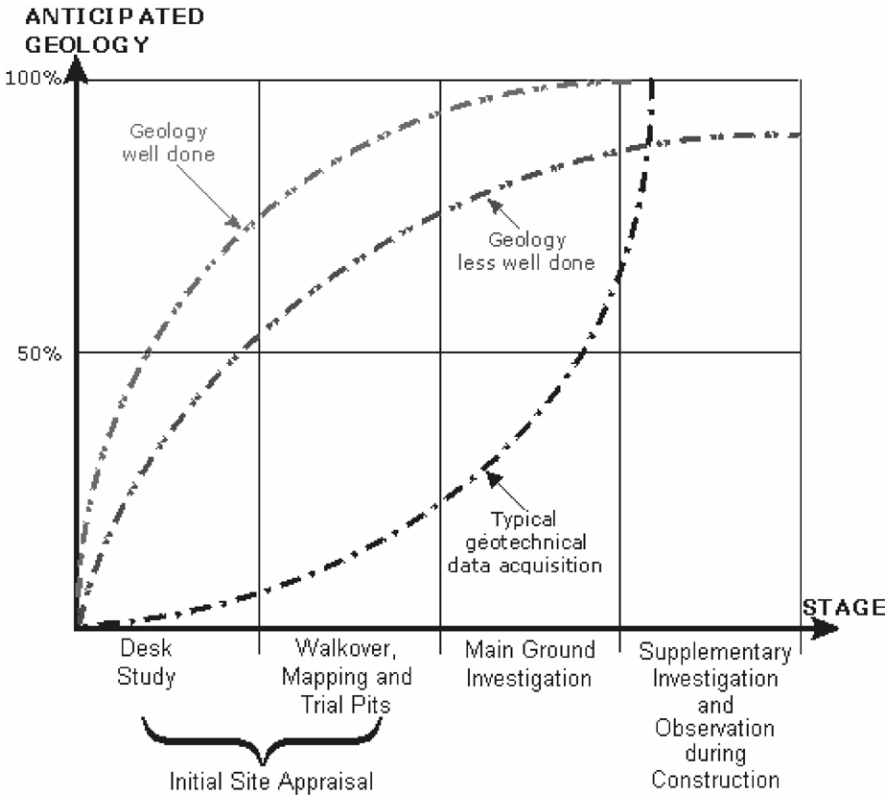

Figure 21.1. Site investigation stages, after Fookes et al. (2001)

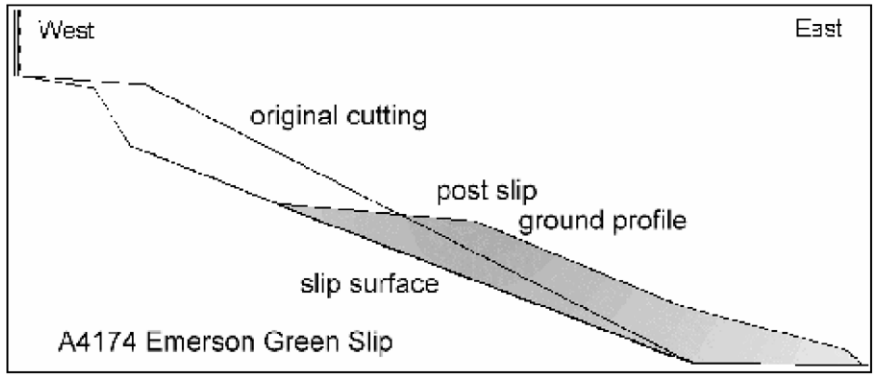

Figure 21.2. The Emerson Green slip

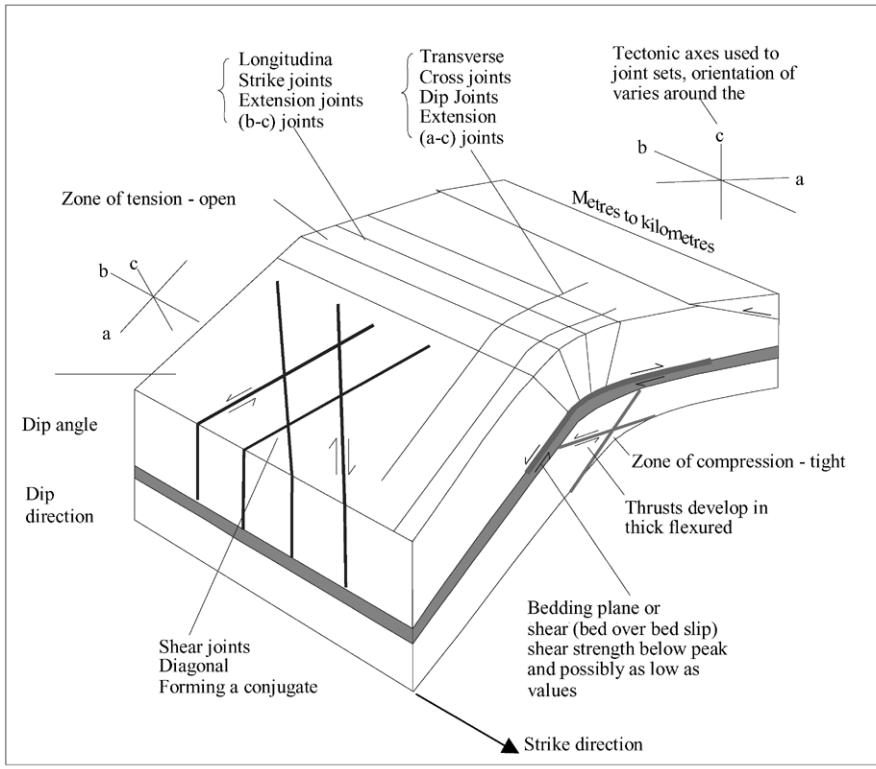

Figure 21.3. Geological model – structural – open folds and joints (after Fookes et al., 2001, figure 3.12)

Table 21.1. The geological environment matrix

Rock forming Environments		
Principal environment	Main sub-environment	Key
Continental	Slopes	1.1
	Glacial	1.2
	Proglacial	1.3
	Periglacial	1.4
	Drylands	1.5
	Wetlands	1.6
	Lacustrine	1.7
	Fluvial	1.8
	Esturine	1.9
	Costal	1.10
Marine	Lagoonal	2.1
	Reef	2.2
	Shelf	2.3
	Cont. slope	2.4
	Abyssal	2.5
Igneous	Plutonic	3.1
	Intrusive	3.2
	Extrusive	3.3
	Pyroclastic	3.4
	Hydrothermal	3.5
Metamorphic	Temperature	4.1
	Pressure	4.2
	Regional	4.3
	Auto	4.4

Rock modifying environments		
Principal environment	Main sub-environment	Key
Burial	Compaction	Aa
	Diagenesis	Ab
	Metamorphism	Ac
Techtonic	Folding	Ba
	Faulting / shearing	Bb
	Metamorphism	Bc
Volcanic	Hydrothermal	Ca
	Baking	Cb
Weathering	Periglacial	Da
	Temperate	Db
	Dry tropical	Dc
	Wet tropical	Dd
Processes	Back wearing	Ea
	Down wearing	Eb
	Solution	Ec
	Subsidence	Ed
	Sea level change	Ee
	Earthquake	Ef

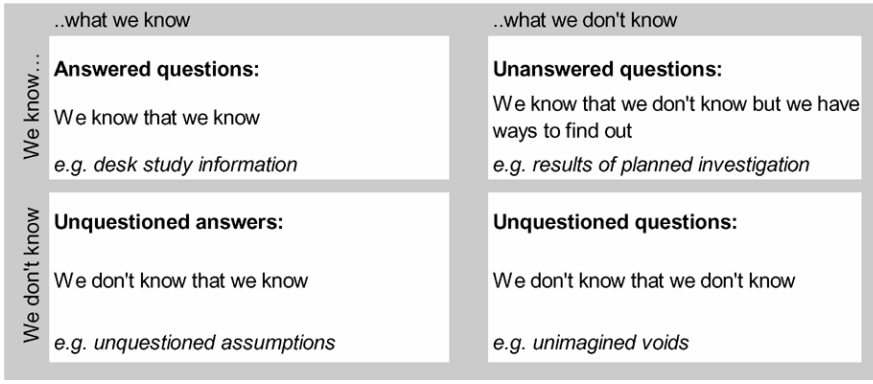
..what we know
..what we don't know
We know...
Answered questions:
We know that we know
e.g. desk study information
Unanswered questions:
We know that we don't know but we have ways to find out
e.g. results of planned investigation
We don't know
Unquestioned answers:
We don't know that we know
e.g. unquestioned assumptions
Unquestioned questions:
We don't know that we don't know
e.g. unimagined voids

Figure 21.4. Knowing what we know

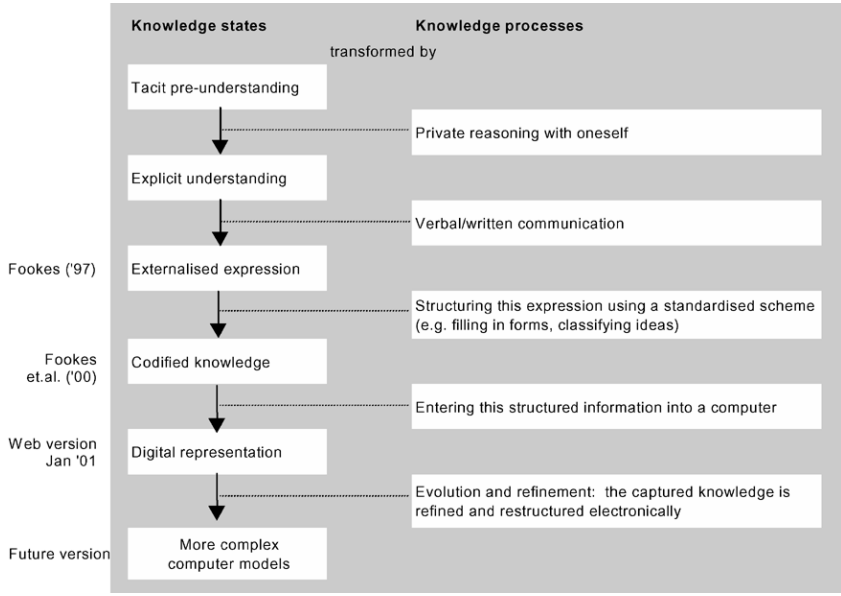

Figure 21.5. Transformation of knowledge from tacit to explicit computer-based knowledge (after Stahl, 1993)

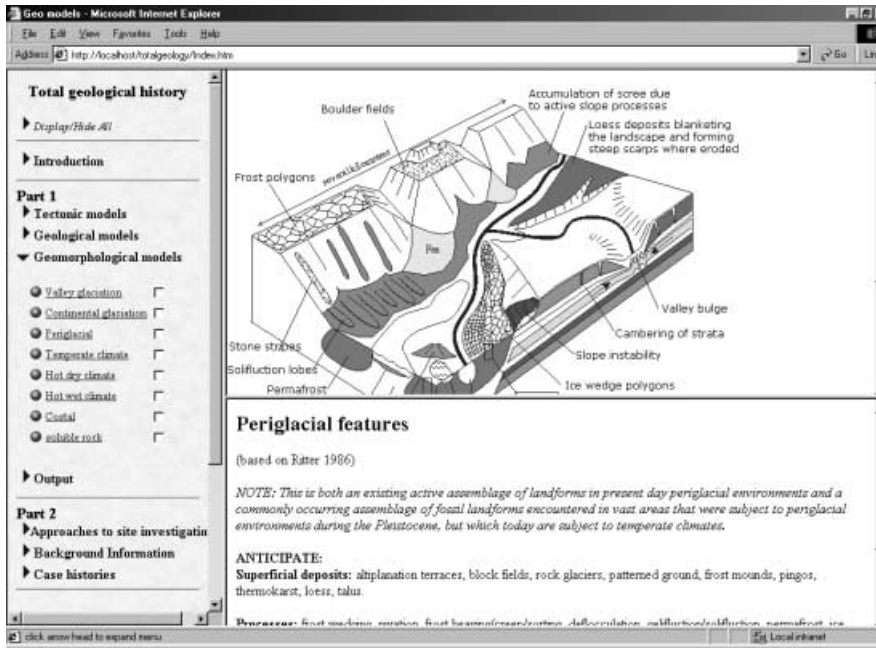
Geo models - Microsoft Internet Explorer
Total geological history
Display/Hide All
Introduction
Part 1
Tectonic models
Geological models
Geomorphological models
Valley glaciation
Continental glaciation
Periglacial
Temperate climate
Hot dry climate
Hot wet climate
Coastal
soluble rock
Output
Part 2
Approaches to site investigatio
Background Information
Case histories
Boulder fields
Accumulation of scree due to active slope processes
Loess deposits blanketing the landscape and forming steep scarps where eroded
Frost polygons
Valley bulge
Cambering of strata
Slope instability
Stone stripes
Solifluction lobes
Permafrost
Ice wedge polygons
Periglacial features
(based on Ritter 1986)
NOTE: This is both an existing active assemblage of landforms in present day periglacial environments and a commonly occurring assemblage of fossil landforms encountered in vast areas that were subject to periglacial environments during the Pleistocene, but which today are subject to temperate climates.
ANTICIPATE:
Superficial deposits: altiplanation terraces, block fields, rock glaciers, patterned ground, frost mounds, pingos, thermokarst, loess, talus.

Figure 21.6. Screen layout : http://www.uwe.ac.uk/geocal/totalgeology

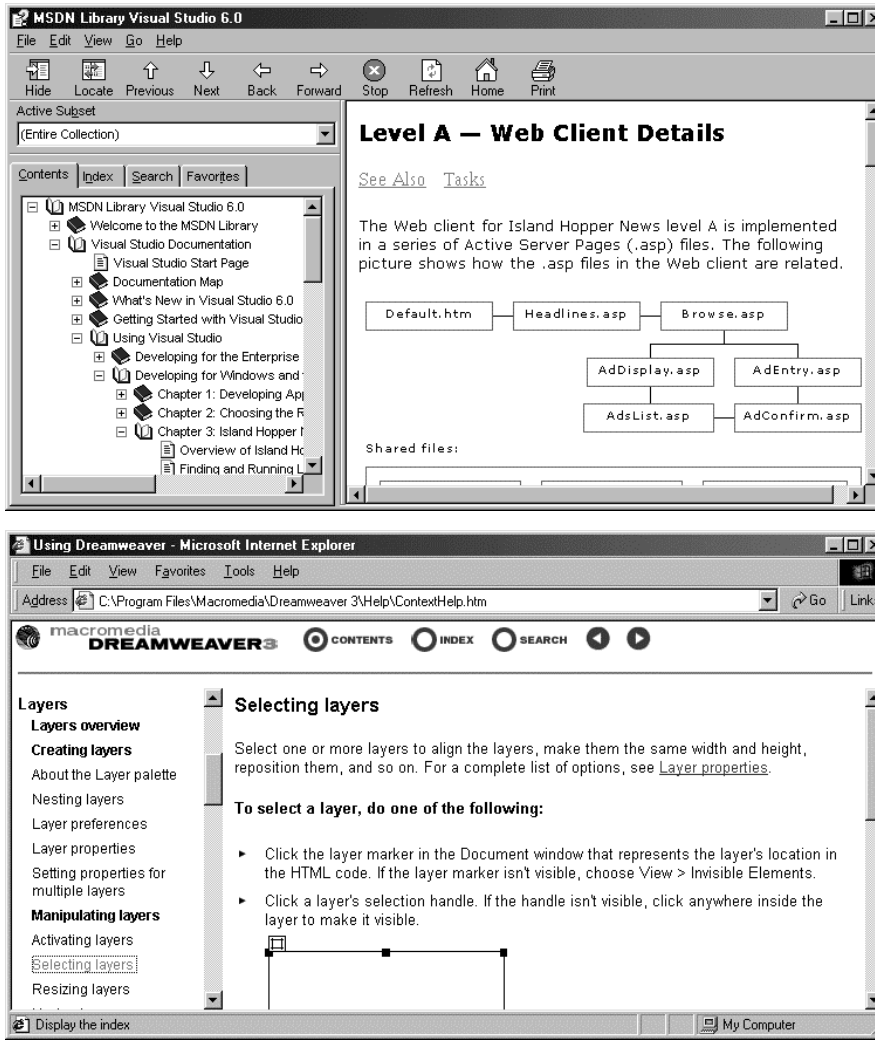
MSDN Library Visual Studio 6.0
File Edit View Go Help
Hide Locate Previous Next Back Forward Stop Refresh Home Print
Active Subset
(Entire Collection)
Contents Index Search Favorites
MSDN Library Visual Studio 6.0
Welcome to the MSDN Library
Visual Studio Documentation
Visual Studio Start Page
Documentation Map
What's New in Visual Studio 6.0
Getting Started with Visual Studio
Using Visual Studio
Developing for the Enterprise
Chapter 1: Developing Ap
Chapter 2: Choosing the R
Chapter 3: Island Hopper
Overview of Island Hc
Finding and Running L
Level A — Web Client Details
See Also Tasks
The Web client for Island Hopper News level A is implemented in a series of Active Server Pages (.asp) files. The following picture shows how the .asp files in the Web client are related.
Default.htm
Headlines.asp
Browse.asp
AdDisplay.asp
AdEntry.asp
AdsList.asp
AdConfirm.asp
Shared files:
Using Dreamweaver - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Address C:\Program Files\Macromedia\Dreamweaver 3\Help\ContextHelp.htm
Go Links
macromedia DREAMWEAVER3
CONTENTS INDEX SEARCH
Layers
Layers overview
Creating layers
About the Layer palette
Nesting layers
Layer preferences
Layer properties
Setting properties for multiple layers
Manipulating layers
Activating layers
Selecting layers
Resizing layers
Selecting layers
Select one or more layers to align the layers, make them the same width and height, reposition them, and so on. For a complete list of options, see Layer properties.
To select a layer, do one of the following:
Click the layer marker in the Document window that represents the layer's location in the HTML code. If the layer marker isn't visible, choose View > Invisible Elements.
Click a layer's selection handle. If the handle isn't visible, click anywhere inside the layer to make it visible.
Display the index
My Computer

Figure 21.7. Two examples of commercial web based information systems for professional users

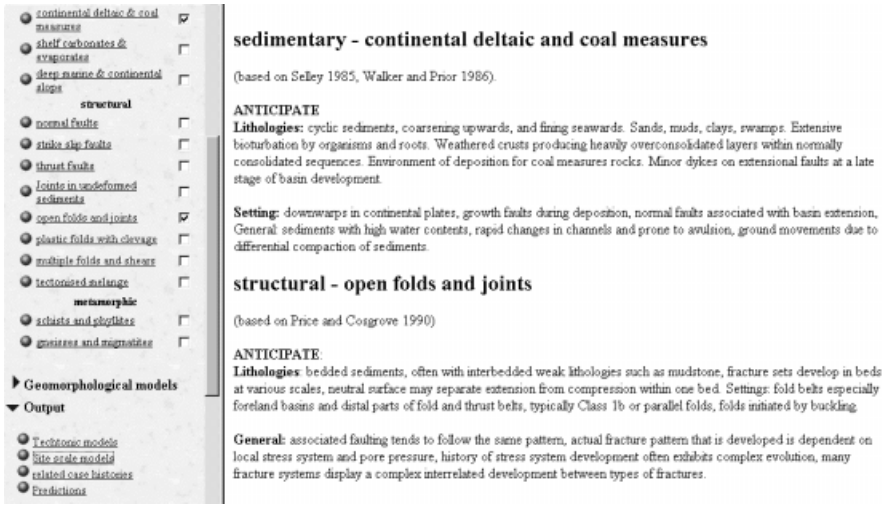
continental deltaic & coal measures
shelf carbonates & evaporates
deep marine & continental slope
structural
normal faults
strike slip faults
thrust faults
joints in undeformed sediments
open folds and joints
plastic folds with clevage
multiple folds and shears
tectonised melange
metamorphic
schists and phyllites
gneisses and migmatites
Geomorphological models
Output
Tectonic models
Site scale models
related case histories
Predictions
sedimentary - continental deltaic and coal measures
(based on Selley 1985, Walker and Prior 1986).
ANTICIPATE
Lithologies: cyclic sediments, coarsening upwards, and fining seawards. Sands, muds, clays, swamps. Extensive bioturbation by organisms and roots. Weathered crusts producing heavily overconsolidated layers within normally consolidated sequences. Environment of deposition for coal measures rocks. Minor dykes on extensional faults at a late stage of basin development.
Setting: downwarps in continental plates, growth faults during deposition, normal faults associated with basin extension, General: sediments with high water contents, rapid changes in channels and prone to avulsion, ground movements due to differential compaction of sediments.
structural - open folds and joints
(based on Price and Cosgrove 1990)
ANTICIPATE
Lithologies: bedded sediments, often with interbedded weak lithologies such as mudstone, fracture sets develop in beds at various scales, neutral surface may separate extension from compression within one bed. Settings: fold belts especially foreland basins and distal parts of fold and thrust belts, typically Class 1b or parallel folds, folds initiated by buckling.
General: associated faulting tends to follow the same pattern, actual fracture pattern that is developed is dependent on local stress system and pore pressure, history of stress system development often exhibits complex evolution, many fracture systems display a complex interrelated development between types of fractures.

Figure 21.8. Check boxes used to select models

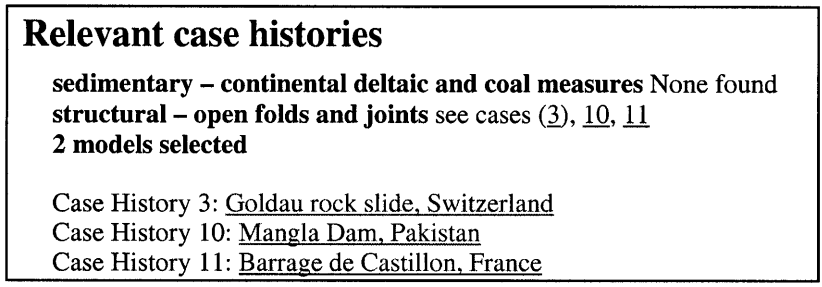
Relevant case histories
sedimentary – continental deltaic and coal measures None found
structural – open folds and joints see cases (3), 10, 11
2 models selected
Case History 3: Goldau rock slide, Switzerland
Case History 10: Mangla Dam, Pakistan
Case History 11: Barrage de Castillon, France

Figure 21.9. Related case history output

22 3D modelling system for ground engineering

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22.1 Introduction

Three-dimensional geo-information systems (3D GIS) provide the tools for enabling interactive construction of volumetric models of the ground profile. These permit analysis and interpolation of geological characteristics, facilitating appraisal of the engineering problem to hand (Turner, 1992, Orlic and Hack, 1994).

However, 3D GIS are not well suited to decision support. There is a need to combine the powerful visualisation technologies with decision analysis and artificial intelligence software. 3D subsurface modelling applications are discussed from a decision making perspective for two case studies which typify ground engineering.

22.2 Case Study 1: Foundations

The selection of foundation type is determined by the regional estimation of soil settlement, aided by geometrical modelling, visualisation and geostatistical analysis. Finite Element Modelling (FEM) enables surface or volumetric representation through the use of nodes generated from control data (boundary conditions).

The goal is to correctly select the foundation type and design a cost effective and safe foundation. The basic need for this decision-making problem is access to appropriate information regarding the subsurface conditions and the ground-structure interaction. These can be listed as geological information (depth, extent, thickness of layers), geotechnical information (soil/rock engineering properties, unit weight, cone resistance), and information regarding the behaviour of the ground when subject to a change in equilibrium.

The present 3D GIS technology provides tools and techniques to model the structure but treats the subsurface as a continuous distribution within the volume of interest. Traditional design practice assigns an averaged sample value using the statistical mean, leading to a somewhat conservative design and consequently higher foundation cost.

The foundation engineer uses soil/rock mechanics models to predict the reaction of the ground subjected to loading. The 3D geological and geotechnical models provide the ground parameters to the soil mechanics models.

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Saturated soils undergo a volume change under application of a steady load (due to the weight of overlying earth material or manmade structures, or from the lowering of the water table). The volume change (a decrease in volume) in the soil mass is the result of dissipating water to restore an equilibrium stress state.

A settlement model may be based on the modified Terzaghi equation (Koopejan equation, CUR, 1996) and uses the following relationship:

$$S = \frac{H}{C'} ln \frac{\sigma'_v + \Delta p}{\sigma'_v} \qquad [1]$$

Where,

S = settlement (m)

H = thickness of the compressible layer (m)

C′ = the coefficient of compressibility

σ′v = the initial vertical effective stress at the mid-height of the compressible layer (kPa)

Δp = increase in vertical effective stress (kPa).

The total settlement is thus a direct result of the subsurface geometry and the geotechnical properties of the soil masses. The vertical displacement is calculated at the mid-height of the compressible layer (the centre of the 3D grid cell). By adding the individual displacements from bottom to top (3D grid column), the total settlement at any depth is obtained.

The geometrical modelling of the ground is based on cross-sections derived from the geological map, boreholes and CPT soundings (Orlic, 1997). The Lynx geoscience modelling system has been used for the modelling tasks (Houlding, 1994). Using Lynx, data is stored in a 3D database projected to user-selected planes to delineate polygonal boundaries of each geological unit. These are connected by links to form solid volumes. Subsequent 3D model building based on the surfaces is tedious and time consuming, and impossible where the geology is complex or discontinuous.

To overcome the drawbacks, a measure of certainty (confidence level) can be assigned to the user-interpreted boundaries. This sort of functionality allows the user to incorporate his belief regarding the model.

The 3D geotechnical model is constructed in a comparable manner, as a continuous distribution utilising grid cell dimensions of 10 m x 10 m horizontal (N–S and E–W) and 1 m vertical (depth). This grid is intersected with the volume model of soil units to provide the data structure suited to spatial analysis and geotechnical characterisation (Figure 22.1). The 3D grid data structure supports the geological controls on the interpolation and calculation routines and provides a continuous distribution of the parameter of geotechnical interest.

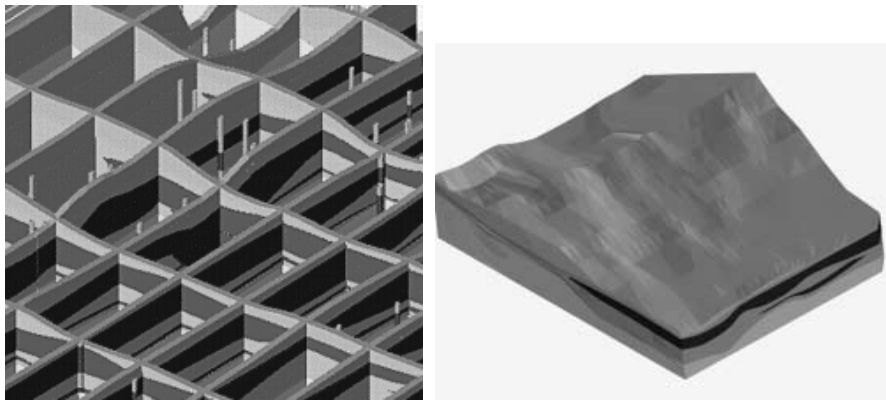

Figure 22.1. Geological modelling; fence diagram (left) and solid volume model (right) of soil profile

Using the geostatistical modelling routines in Lynx, the distribution of cone resistance values within the modelled volume may then be predicted. The prediction is made using ordinary volume kriging on log-transformed sample values. The geostatistical modelling process first involves a statistical analysis of measured sample values in terms of primary statistics, histogram and probability analysis. The anisotropy, directional trends and data transformations are then tried and the variography conditions tested. If a measurable spatial variability of sample values is identified then the variogram models can be constructed. The details of variography and the geostatistical interpolation techniques are contained in standard texts (e.g. Myers, 1997).

The 3D settlement may then be calculated at the centre of each cell by applying a volume weighted average algorithm. The procedure is illustrated in Figure 22.2.

The major problem experienced concerned the data exchange between the 3D modelling and FEM packages. The number of nodes in the exported file was too high for the FEM package to effectively generate a finite element mesh. In addition, the thin layers and lenses modelled in the 3D system could not be regenerated in the FEM geometry especially when the length to depth ratio of the section is high.

The analysis of settlement using 3D GIS resulted in a realistic picture of settlement predictions (Figure 22.3).

22.3 Case Study 2: Tunnels

The second case study concerns ground characterisation for tunnelling in soft soils. The engineering requirements are to determine the volumes of each soil type to be encountered and to estimate their geotechnical properties, water pressures and likely surface settlements. The first two requirements are satisfied with the available 3D modelling functions with little use of external routines. The third requirement could only be partially satisfied with extensive use of external routines.

A multi-attribute dynamic functional analysis capability is required on vertical grid-sections of predefined thickness.

The geological modelling was based on a site investigation comprising 62 Cone Penetration Tests (CPTs) and 11 boreholes with associated sampling. Lynx was again employed, but the geological complexity meant that only manual modelling could be used (Lynx, 1997). Two main sets of cross sections were drawn to define the geological unit boundaries, aided by fence-diagrams linked to form a solid volume model (Figure 22.4). The accurate volume modelling had decisive impact (Figure 22.5). The inclusion of geological semantics facilitated provision of technical advice delineating each unit's polygonal boundaries.

Geotechnical modelling was based on the site investigation data and the results of laboratory tests on soil samples. The data scarcity restricted the use of geostatistical interpolation as an option. Only the inverse distance interpolation of a few geotechnical variables could be achieved. In most instances the assignment of geotechnical parameters was done by using a knowledge-based system, i.e. reasoning on the basis of engineering geological knowledge by an expert (preferences and rules) (Attewell and Toll, 1990).

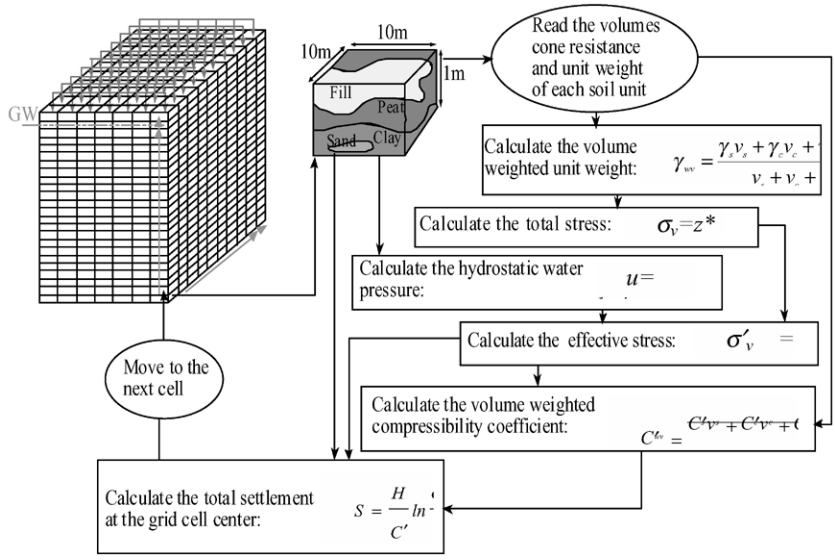
GW
10m
10m
1m
Fill
Peat
Sand
Clay
Read the volumes cone resistance and unit weight of each soil unit
Calculate the volume weighted unit weight:
Calculate the total stress: $\sigma_v = z^*$
Calculate the hydrostatic water pressure: $u =$
Calculate the effective stress: $\sigma'_v =$
Calculate the volume weighted compressibility coefficient:
Move to the next cell
Calculate the total settlement at the grid cell center: $S = \frac{H}{C'} ln$

Figure 22.2. The conceptual diagram of settlement modelling system

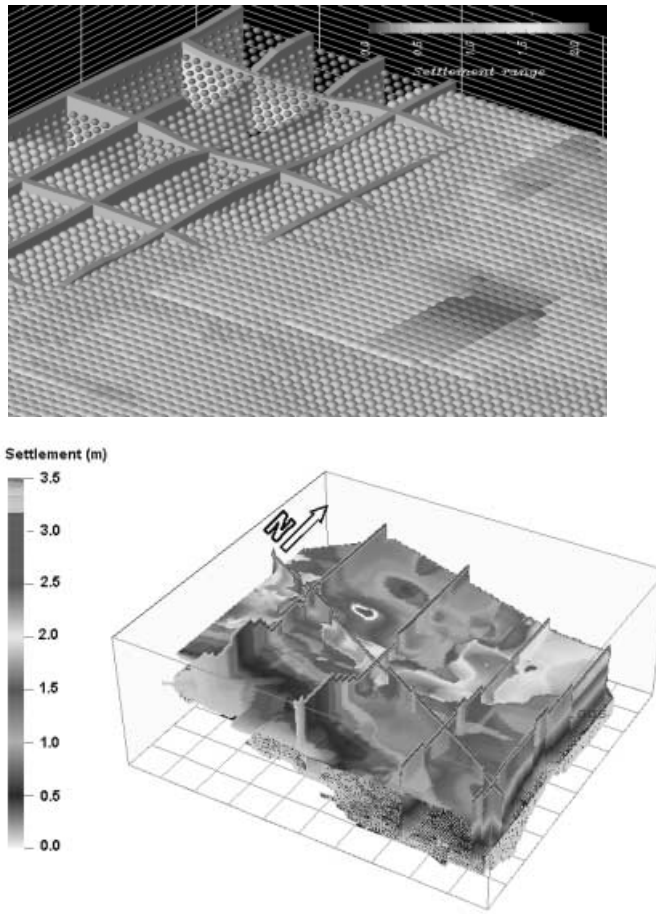

Figure 22.3. The 3D visualisation of settlement ; settlement glyphs (upper) and iso-volumes of settlement range (lower)

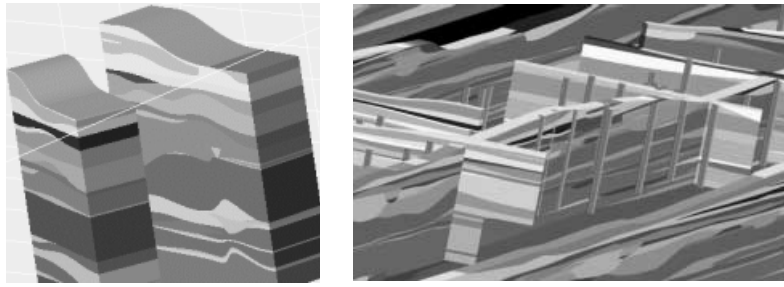

Figure 22.4. Geological modelling: interpreted cross-sections (left) and fence diagram with soundings (right)

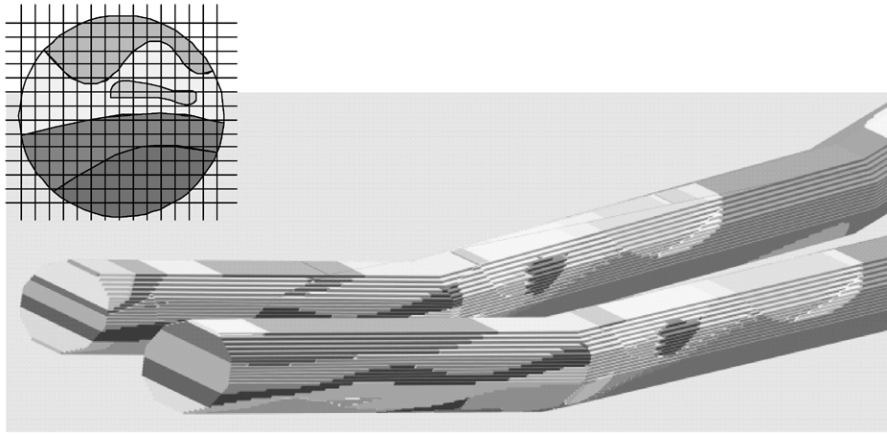

Figure 22.5. Intersection of the tunnel structure with the volumetric model displaying the geology, with an inset to show a single element to be excavated or considered for settlement analysis

The representation of expert knowledge can be accomplished with rules and symbolic functions. LispWorks-KnowledgeWorks (1997), a commercial Lisp-based system, was used for the application. An example of an expert rule assigning values to project variables follows, updating the information-base, and interfacing the user with other applications:

```
(defrule settlement_risk_10 : priority 2
(voxel ?grid-object soil_type ?soil_type, tbm_type ?tbm_type,
tunneling_depth, ?tunneling_depth, tunnel_diameter ?tunnel_diameter,
surface_surcharge ?surface_surcharge, water_table ?water_table)
        (Test (equal ?soil_type clay))
        (Test (equal ?tbm_type EPBS))
        (Test (>= ?tunneling_depth 16)) .....
->
(assert (voxel ?grid-object "settlement likely"))
(update-information-base ?grid-object) (capi:confirm-yes-or-no "Do you want
to visualize the results now"))
```

Such algorithms are used for decision tree generation and knowledge extraction from the available data (Figure 22.6). These include inductive learning, back-propagation, Bayes classification, and case-based reasoning. Details are provided by Quinlan (1993), Taylor et al. (1994), and Kohavi et al. (1996). The algorithms spot patterns or relationships in the data, and then extract knowledge in terms of rules and decision trees (Table 22.1).

22.4 Conclusions

The two case studies have demonstrated some of the capabilities of 3D GIS as a modelling and problem-solving tool for civil engineering projects. The current state of 3D GIS technology nevertheless has shortcomings. In terms of volume representation and property analysis, the detail required in the shallow subsurface characterisation for construction and the efficiency in handling such detail have not yet reached a desirable level. Moderately complex mathematical calculations and the incorporation of accepted rock/soil mechanics models are not yet supported. The ease of exchange of model structures between 3D GIS and FEM applications is limited to simple situations, but can nevertheless facilitate the effective use of subsurface information in the design and construction stages. An integrated system of tools and techniques from 3D GIS, improved visualisation and artificial intelligence components will bring the necessary power and functionality to support effective decision making in large ground engineering projects.

Table 22.1. Categorical attributes for training the knowledge-based system

a) a simplified table of categorical attributes (structure)

ATTRIBUTE	POSSIBLE VALUES
Geology	sand, clay, peat
Permeability	unknown, low, medium, high
CPT	unknown, range A, range B, range C, range D

b) a simplified table of training set [When the structure (a) and the training set are provided, the complete test set (unclassified data) including millions of instances can be induced]

GEOLOGY	PERMEABILITY	CPT	CLASS
Sand	Unknown	unknown	class 1
Peat	Medium	range A	class 6
Peat	High	range C	class 4
Clay	Unknown	unknown	class 2
Peat	High	range B	class 3
Peat	High	range D	class 5

c) a decision tree model for the training set in (b)

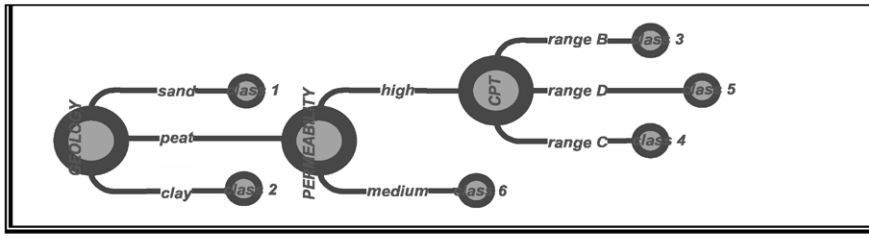

Figure 22.6. Stages of machine learning and the rule induction process

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23 Rock mass quality assessment based on deformation: experience from recent tunnels

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23.1 Introduction

The excavation of a tunnel re-arranges the stress field around the void, which tends to close due to the weight of the overlying rock mass. Tunnel closure is proportional to the void dimensions. For large tunnels (with a radius larger than 10 m and a length longer than 250 m), this takes the form of either a reduction of the tunnel section or a partial or total collapse (Figure 23.1), and thus represents a threat for excavation.

An attempt is made in this paper to establish the suitability and adequacy of a Geological Strength Index (GSI) in characterising various rock types, including those with low strength and high deformability (Hoek, 1994; Hoek and Brown, 1998). Tunnel closure is an especially important consideration in the case of low-strength rocks having a GSI less than 25, and where there is a thick (hundreds of metres) overburden (Kovari et al., 1993).

Strain values in excess of 2% require a special consideration in terms of support. Higher values may significantly reduce the tunnel diameter (Sakurai, 1983), making necessary its re-excavation; a process producing delays and a dramatic increase in cost of the work.

23.2 Design approach

The first approach to designing and economic and safe underground opening is to establish the geological conditions. Several rock mass quality rating systems have been introduced for such characterisation. The most popular are the Rock Mass Rating (RMR) system introduced by Bieniawski (1973, 1979) and the NGI (Q) system (Barton et al., 1974, 1988, 1994). Both the RMR and Q systems use the parameter Rock Quality Designation (RQD) and the compressive strength of the intact rock material ($\bullet_{ci}$) for estimation of the rock mass quality; both parameters are deduced from ground investigation.

Poor quality rock yields relatively few intact core pieces longer than 100 mm and hence it is difficult to determine either the RQD or the $\bullet_{ci}$ parameter. This

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makes it difficult to calculate a reliable RMR or Q value (Hoek and Brown, 1998). In addition, both methods have been formulated from tunneling experience on fair to good quality rock masses (Xidakis, 1994; Marinos, 1994) so limiting their applicability to lower quality ground.

More recently (Hoek, 1994; Hoek et al., 1995) the Geological Strength Index system has been introduced to characterise the rock mass. This is based on the visual impression of the rock structure (blockiness and surface condition). GSI can be applied to lower quality rock masses since it does not necessitate sampling. However, several rock mass types are difficult to describe by the GSI approach: weak rocks of low strength and high deformability, and sheared, folded, faulted, and mylonitised rocks (Hoek et al., 1998).

The key question concerns the success with which GSI can be applied. This question is now considered using data from five recent tunnels in Greece, excavated in rock masses where GSI ranges from 15 to 65 at depths in the range 45 to 120 m.

Data from the fifth tunnel (Tymfristos) excavated in very low quality ground could not be classified according to the existing rating system. Extensive convergence occurred, and an 'equivalent GSI value', GSI_e, has thus been introduced. This parameter is deduced from an inverse analysis of the tunnel deformation during or shortly after the excavation. The analysis uses the 'characteristic line' method (Hoek,1999) for predicting tunnel deformation.

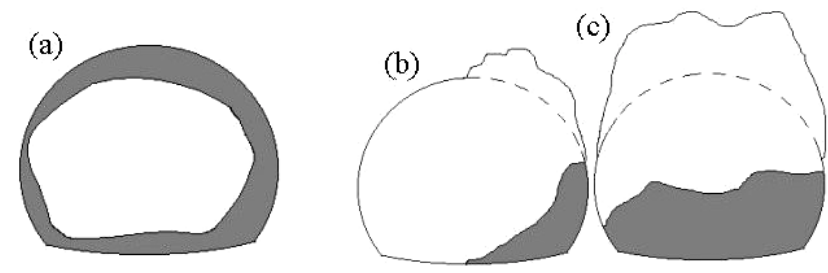

Figure 23.1. Tunnel deformation: **(a)** reduction of the tunnel section, **(b)** partial collapse, **(c)** total collapse. Shading indicates mass intruding the excavated area. After Kovari and Amstad (1993)

23.3 Prediction of tunnel convergence

Having characterised the rock mass, the next step is to design the support system and predict the expected deformation. Prediction of tunnel convergence is usually based on two different approaches. The first approach is based on the theory of a 'characteristic line' (Hoek, 1999), an approximate method computing tunnel convergence and the thickness of the plastic zone produced during excavation. This theory is based on the following assumptions: (i) the tunnel section is circular and (ii) the stress field along the tunnel periphery is constant.

In the second approach, prediction of the tunnel closure is made on the basis of a numerical analysis. Current practice utilises a 2D plastic Finite Element Modelling (FEM) approach and the PHASES software (Rocscience, 2000). This software permits a 2D study of non-linear deformation of rock, using both the Mohr-Coulomb criterion for low quality material and the Hoek-Brown failure criterion for better quality rock (Hoek and Brown, 1998).

In the present analysis the 'characteristic line' method does not take into account the support system capacity. Therefore, the predicted deformation using the 'characteristic line' is expected to be larger than the convergence predicted using FEM or the actual deformation during tunnel excavation, since a temporary support system was usually installed.

23.4 Monitoring tunnel convergence

Tunnel deformation has in the past been usually measured with INVAR tapes and wires (Kovari et al., 1993). These can only measure changes in the distance between selected points fixed on the tunnel periphery and provide an accuracy of 0.13 mm over 10 m (Dunnicliff, 1993). More recently, geodetic techniques have permitted the monitoring of both the reduction of the tunnel radius and the subsidence of its roof. These techniques are simple, inexpensive, functional and do not cause delays to the advancing excavation works. Measurements are based on the principles of tacheometry utilising 'total station' geodetic instruments. Measurements are taken periodically (usually once per day) until stabilisation of the height of all targets is obtained, usually over a two-month period (Kontogianni et al., 1999).

A comparison between predicted and observed radius reduction was made in five tunnels. These employ the GSI parameter and the values of vertical strain. All tunnels studied have approximately the same diameter (10–12 m). The main parameters differing between each case study are the quality of the surrounding rock mass and the type of temporary support employed. The expected convergence for each tunnel was predicted using the 'characteristic line' calculation (Hoek, 1999) and FEM.

Figure 23.2 summarises predicted and observed initial strain relative to the GSI of the rock masses for the five tunnels. Strain is computed as the ratio of ceiling subsidence to the tunnel diameter, so that data from tunnel sections with a different diameter are comparable. The main outcome is that the convergence values seem to follow exponential curves for the two tunnelling depths. Refer to Kontogianni et al. (2002) for a detailed analysis of the deformation, taking into account the support systems.

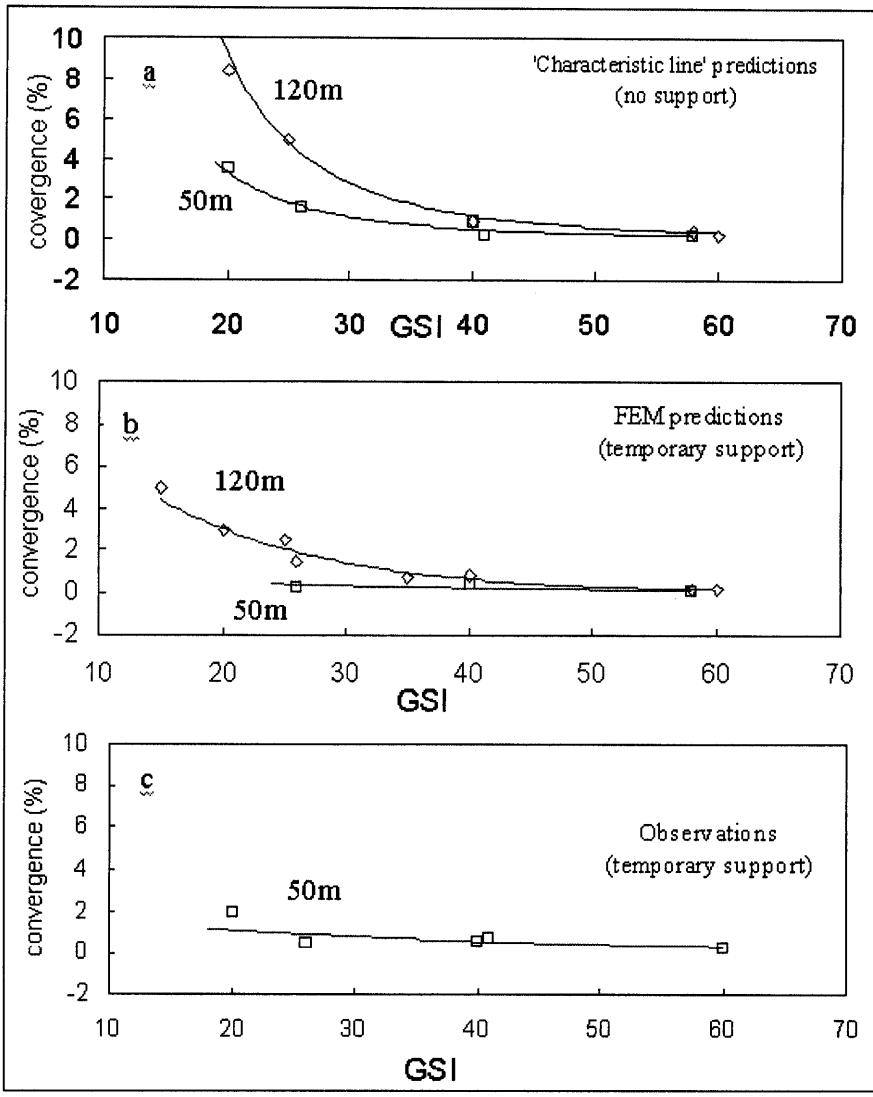

Figure 23.2. Predicted and observed tunnel convergence plotted against GSI: **(a)** predicted tunnel convergence based on the characteristic line method (Hoek, 1999), **(b)** predicted tunnel convergence (%) based on the Finite Element Method, **(c)** observed tunnel convergence using geodetic techniques. Diamonds indicate the available data for 120 m and squares for 50 m depth. Solid lines are the best fitting exponential lines. After Kontogianni *et al.* (2002)

23.5 Tymfristos tunnel and the equivalent GSI_e

Based on the initial geological and geotechnical studies for the Tymfristos tunnel, the measured RMR parameter of the order of 15–20 indicated a poor to fair quality rock. This would suggest subsidence in the order of 10–70 mm based on the 'characteristic line' theory for an unsupported section. The observed vertical subsidence was much larger: 200–910 mm (Table 23.1).

It is therefore evident that the estimated RMR value roughly corresponding to GSI=30 significantly overestimates the rock mass quality. One possible explanation is that the geotechnical study ignored the rock mass being highly tectonised, and consequently its strength has been significantly reduced.

GSI was designed as parameter for describing better quality rock masses with a minimum GSI value of 25. To overcome this limitation, a new parameter, the equivalent GSI_e has been introduced. This is calculated from an inverse analysis of the available data together with the 'characteristic line' formula.

Table 23.1. Observed and calculated convergence for 10 sections beneath 37 to 94 m overburden in the Tymfristos Tunnel. The computed deformations are based on the initial GSI values, and are substantially lower than those observed. The sections having thick overburden (120–140 m) experienced even larger convergences

Section	Overburden height (m)	RMR	GSI	Calculated convergence (mm)	Observed convergence (mm)
1	37	16	30	14	328
2	51	12	32	9	225
3	60	19	31	16	404
4	68	15	30	37	295
5	72	20	31	21	462
6	83	19	32	16	910
7	84	19	32	17	744
8	89	14	30	62	623
9	93	15	30	68	510
10	94	18	31	32	642

More explicitly, the observed deformation after completion of the tunnel is used as well as the $\bullet_{ci}$ parameter (the intact rock mass strength). The result is an estimate of the value of GSI which correlates with the observed convergence.

The 'characteristic line' analysis, using the two input parameters GSI and $\bullet_{ci}$, is able to predict the convergence. If one of these input parameters lies between two end-point values, the output estimate will accordingly fall between a minimum and a maximum convergence. In the inverse analysis, for any value of the $\bullet_{ci}$ a

curve f., reflecting the relationship between convergence and GSI, is drawn. The common point of this curve and the straight line corresponding to the observed convergence defines the GSI_e value. However, instead of a precise value, a range of σ_{ci} values, between a minimum and a maximum is usually available. For this reason, two f. curves can be constructed and GSI_e will then correspond to any point of a line segment. More explicitly, this segment is defined as the part of the line corresponding to the observed convergence bounded by the two f. curves (Figure 23.3).

The observed convergence is just an upper bound value since this is calculated on the basis of the 'characteristic line' theory, referring to supported sections. Larger deformations would be expected where there is no support. With no support, instead of a line segment bounded by the two f. curves, it is reasonable to consider an areal distribution for GSI_e bounded by the two curves, the line of the observed convergence and a line corresponding to an unknown convergence of the unsupported sections (Figure 23.3).

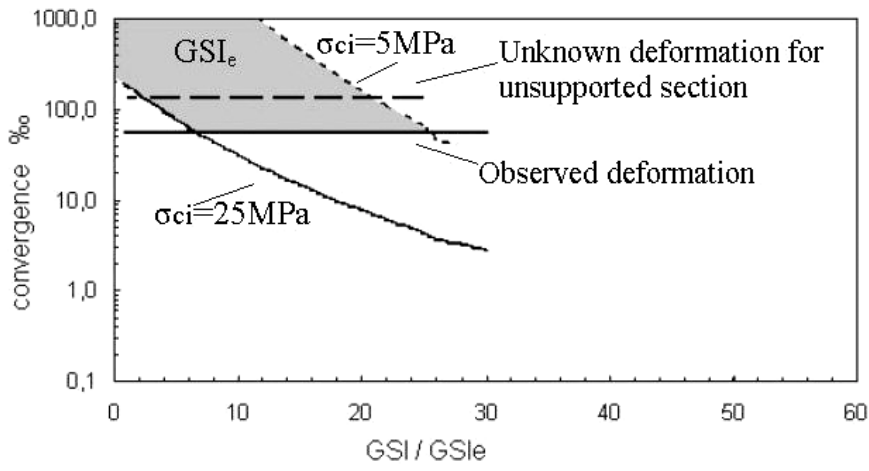

Figure 23.3. Example to estimate GSI_e. Convergence is plotted on a logarithmic scale. The GSI/ GSI_e ratio is deduced from the 'characteristic line' analysis, and values are limited to the shaded zone (after Tzortzis, 2001)

If it is further assumed that the rock mass strength and in situ stress along a specific segment are nearly constant, data from *n* tunnel sections would lead to *n* diagrams similar to Figure 23.3, each with slightly different areas of GSI_e distribution. These areas would normally overlap and their 'centre of gravity' would correspond to the best statistical estimate of GSI_e for the examined segment (i.e. a 'mean' GSI_e). However, given the uncertainties of the data, it is wiser to think of a zone for GSI_e instead of a single value.

This process was applied to a section of the Tymfristos tunnel having similar overburden thickness, σ_{ci}, and lithology. A mean GSI_e of the order of 4–15 corre-

sponding to the shaded zone of Figure 23.4 was computed; these values of GSI_e are extremely low and cannot be classified by the GSI system.

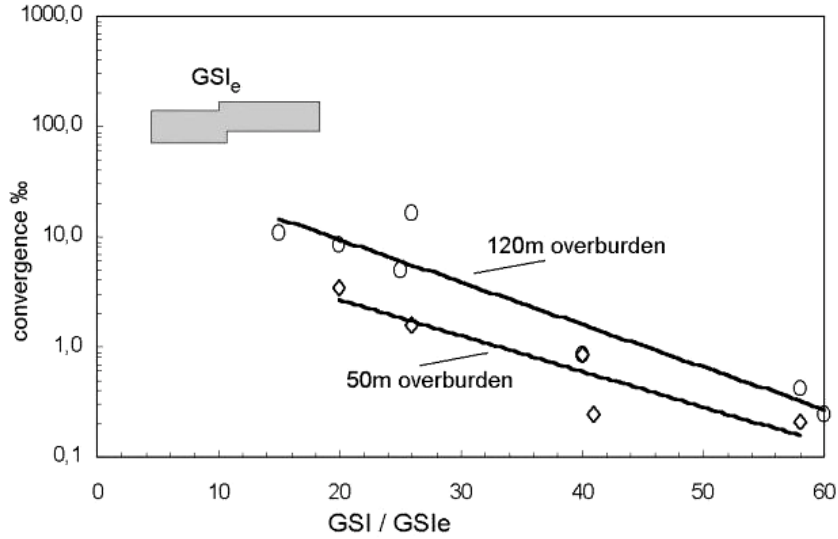

Figure 23.4. Mean GSI_e and observed convergence values for the Tymfristos tunnel (grey area), comparing GSI with convergence (calculated using the 'characteristic line' method) for the five tunnels (using data for Figure 23.2a). The depth of the Tymfristos tunnel lies in the range 37 to 94 m (modified from Tzortzis, 2001)

23.6 Conclusions

The classification of the very weak rock mass characterising the Tymfristos tunnel was achieved by developing the GSI parameter, introducing the equivalent GSI parameter, GSI_e. Based on an inverse analysis using the 'characteristic line' method, deformations and GSI values for different tunnels have been compared. This has yielded a very useful tool for predicting the tunnel behaviour prior to excavation.

Acknowledgments

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24 Improving subsurface parameter estimation through guiding geophysical inversions with *a priori* geological data

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24.1 Introduction

Two-dimensional resistivity inversion is a very popular non-invasive method for imaging the subsurface. The example shown in Figure 24.1 was downloaded from the World Wide Web and illustrates the range of information that can now be obtained. The extensive use of supporting boreholes and the 'smoothness' of the resistivity model are readily apparent.

Resistivity inversion, in common with other geophysical methods, requires a constraint to stabilise the process of deriving a resistivity model from a measurement dataset. The role of the constraint is to ensure 'smoothness' or stability of the solution, or to reflect *a priori* judgements about the likelihood of a solution (e.g. Press et al., 1992). The method of choice for constraining these inversions limits the spatial roughness of the resistivity model, resulting in 'smooth' solutions. This method is often referred to in the geophysical literature as 'smoothness' constrained inversion, being inspired by Occam's razor concerning the merits of the simplest solution (e.g. Constable et al., 1987). However, even at the site scale, the subsurface geology very often varies abruptly with location. For example: dissolution cavities, faults, lithological boundaries and glacial till. Consequently, a smooth resistivity model is often incompatible with subsurface conditions.

The elements of a typical resistivity inversion are shown in Figure 24.2 along with the corresponding matrix equation depicted in Figure 24.3 (e.g. Constable et al., 1987; Sasaki, 1994; Loke and Barker, 1996). This mathematical procedure minimises both the 'data mismatch' and the 'penalty' with the scalar λ controlling the weighting between them. High λ values result in low 'penalties' (smooth resistivity models) and high 'data mismatches'. Conversely, low λ values result in high 'penalties' (rough resistivity models) and low 'data mismatches' (good agreement between 'field' and 'calculated' measurement datasets). Press et al. (1992) describe the role of the constraint in terms of 'regularising or stabilising a highly degenerate optimisation process that would otherwise oscillate between local minima'. Figure 24.4 illustrates their solution space, suggesting the region of 'best' solutions lies in between these two extremes.

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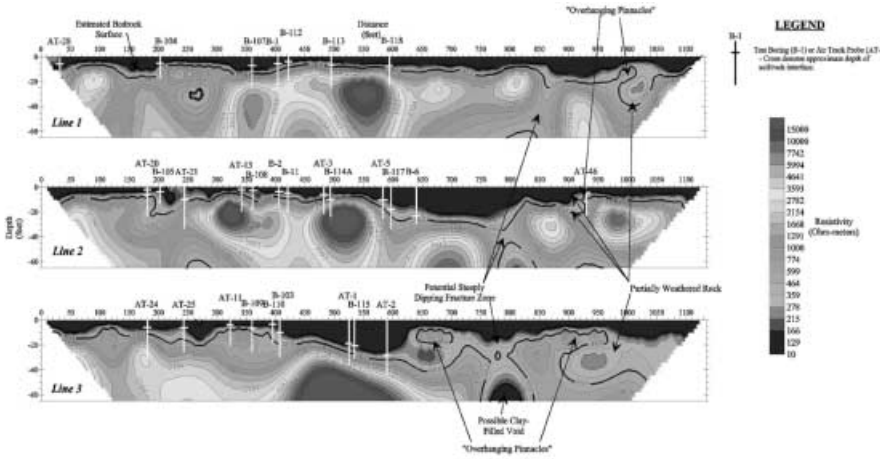

Figure 24.1. Bedrock mapping in karst terrain: an example of subsurface resistivity imaging from the World Wide Web: http://www.agiusa.com/brochure_schnabel_karst.shtml

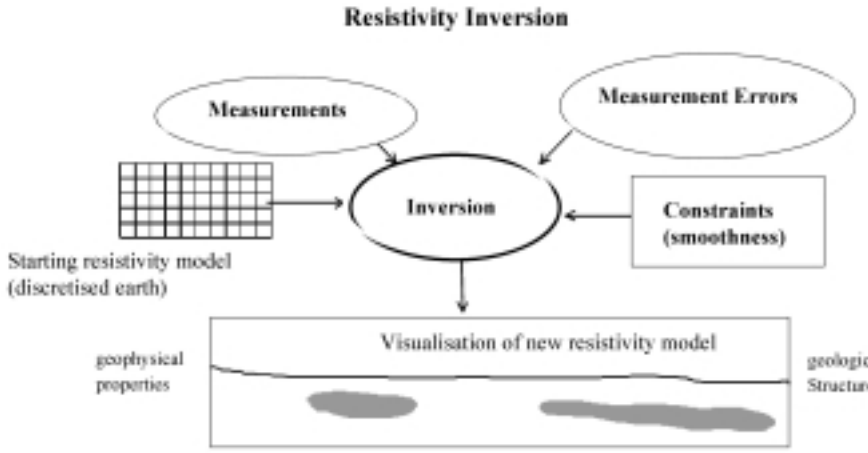

Figure 24.2. Schematic diagram showing the elements of resistivity inversion

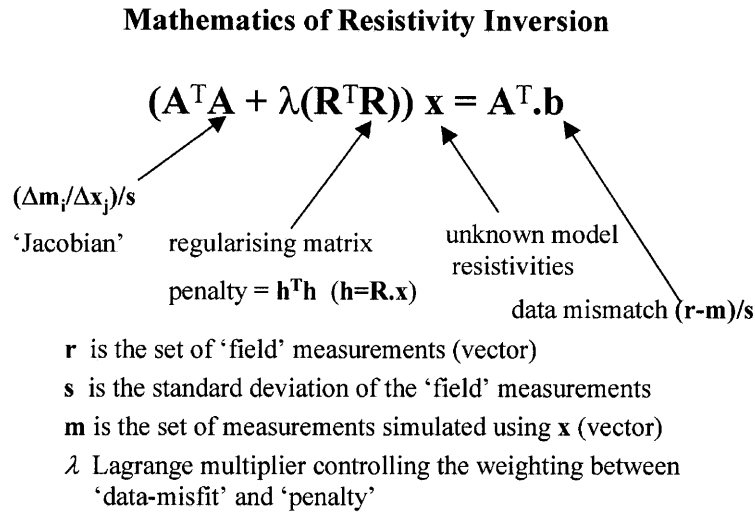
Mathematics of Resistivity Inversion
$(A^TA + \lambda(R^TR))\ x = A^T.b$
$(\Delta m_i/\Delta x_j)/s$
'Jacobian'
regularising matrix
penalty = h^Th (h=R.x)
unknown model resistivities
data mismatch (r-m)/s
r is the set of 'field' measurements (vector)
s is the standard deviation of the 'field' measurements
m is the set of measurements simulated using x (vector)
λ Lagrange multiplier controlling the weighting between 'data-misfit' and 'penalty'

Figure 24.3. A 'smoothness' constrained non-linear least-squares inversion scheme (after Jackson *et al.*, 2001)

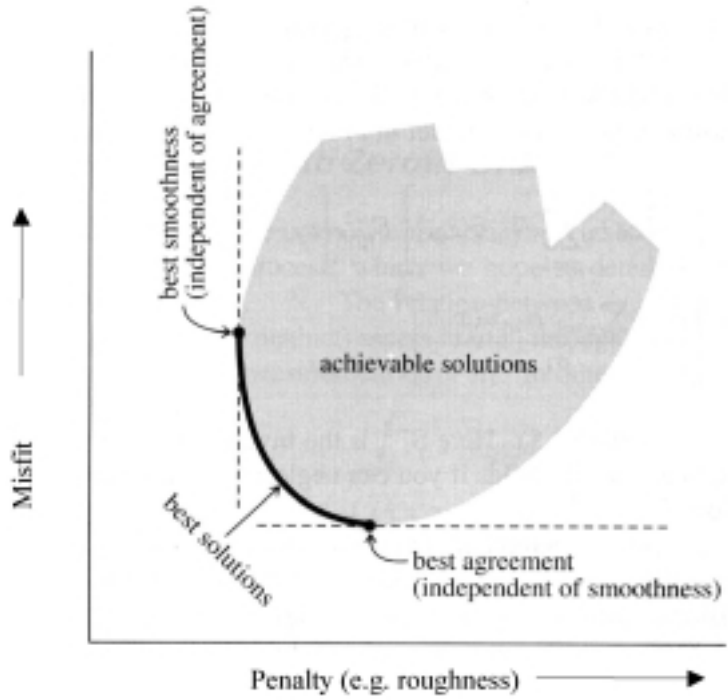

Figure 24.4. The constraint ensures 'smoothness' or stability of the solution, or reflects *a priori* judgements about the likelihood of a solution (adapted from Press *et al.*, 1992)

24.2 Testing Resistivity Inversion

Recently published results of numerical testing of resistivity inversion are illustrated in Figure 24.5. Here, 'field' measurement datasets were calculated for a series of 2D, common, geological ground models: fault without overburden, buried graben and corresponding horst structures (Olayinka and Yaramanci, 2000). Olayinka and Yaramanci inverted these synthetic 'field' data sets using a well known, commercially available, software package RES2DINV (Loke and Barker, 1996). By inspection, the inverted resistivity model can be seen to be far smoother than the resistivity model used to calculate the 'field' measurements, the resistivity values themselves being correspondingly different, of the order of 100% in many cases.

A similar, 3D example of resistivity inversion is illustrated in Figure 24.6. Here a surface array of 200 potential electrodes, at 1 m spacing, can be seen associated with a sub-set of 12 electrodes used to pass current, enabling both components (Ex and Ey) of the resulting electric field to be measured, resulting in over 4000 measurements. The measurement dataset was calculated using the 'true' resistivity model depicted in Figure 24.6 with noise, typical of a greenfield site in the UK, being added to it (Jackson et al., 2001). The results of inversions based on the equation in Figure 24.3 can be seen in Figure 24.7 where the inverted resistivity models using both a coarse and a fine reconstruction mesh are compared. The 'true' resistivity model, shown in Figure 24.6, is compatible with both the coarse and fine meshes. For the coarse mesh, the corresponding inverted resistivity model, having 112 voxels (7 x 4 x 4), is almost identical to the 'true' model.

On the other hand, the inverted resistivity model associated with the fine mesh, having 1170 voxels (13 x 9 x10) can be seen to be significantly different to the 'true' model. Spatial smearing is evident at the base of the resistive structure, and significant 'overshoot' can be seen at higher levels within the structure. For example, resistivity values at the core of the structure at a depth of Z= -4 m can be seen to be 50% too high, and those at a depth of Z= -8 m are in error by 200%. These results, being 'too smooth', are similar to those described by Olayinka and Yaramanci (2000) described above.

As illustrated in Figure 24.8, when considering 'smoothness' constrained inversion, an abrupt spatial change in the resistivity model results in a high 'penalty' while a smooth change results in a low one. Consequently, a high 'penalty' due to a 'step' change in resistivity will be reduced during inversion, in turn leading to a correspondingly smooth inverted resistivity model.

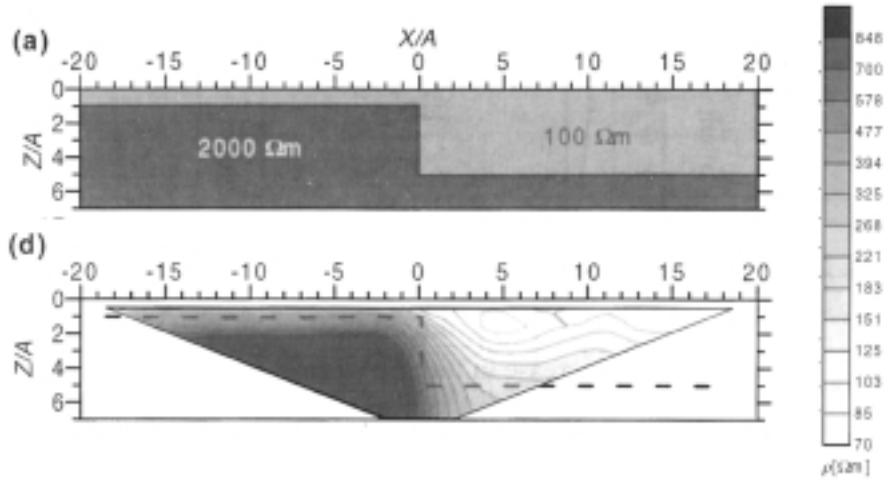

Figure 24.5. 2D numerical experiments (adapted from Olayinka and Yaramanci, 2000)

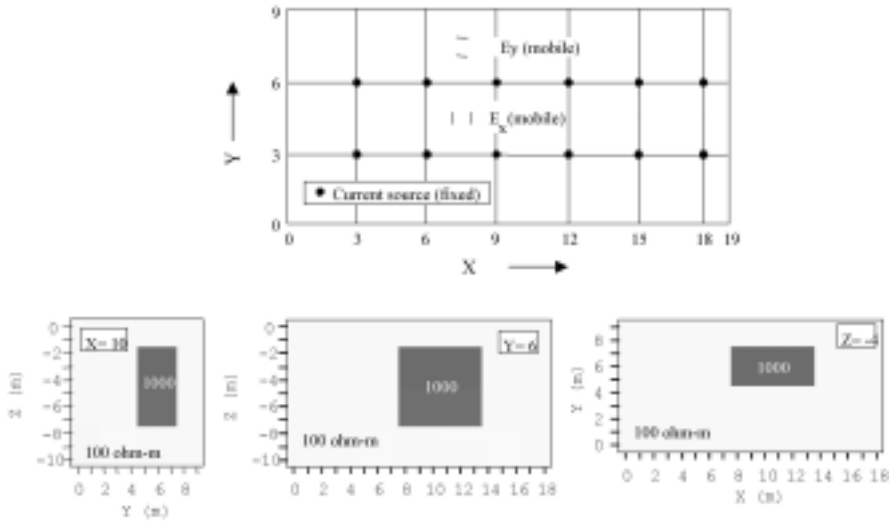

Figure 24.6. Electrode array (X-Y plane) and the 'true' resistivity model used in numerical experiments to test two resistivity inversions (based on Jackson *et al.*, 2001)

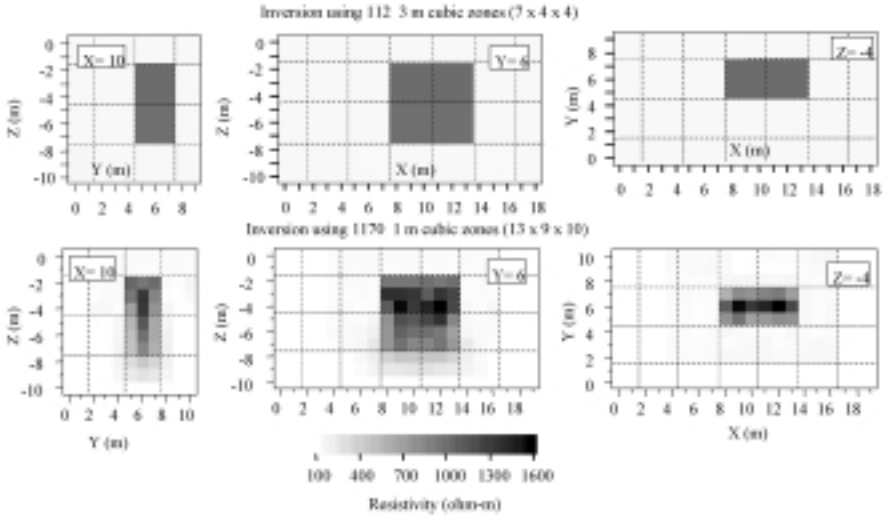
Inversion using 112 5 m cubic zones (7 x 4 x 4)
X= 10
Y= 6
Z= -4
Z (m)
Y (m)
X (m)
Inversion using 1170 1 m cubic zones (13 x 9 x 10)
100 400 700 1000 1300 1600
Resistivity (ohm-m)

Figure 24.7. Resistivity models from inversions using 112 (upper) and 1170 (lower) measurements calculated from the resistivity model shown in Figure 24.6 (based on Jackson *et al.*, 2001)

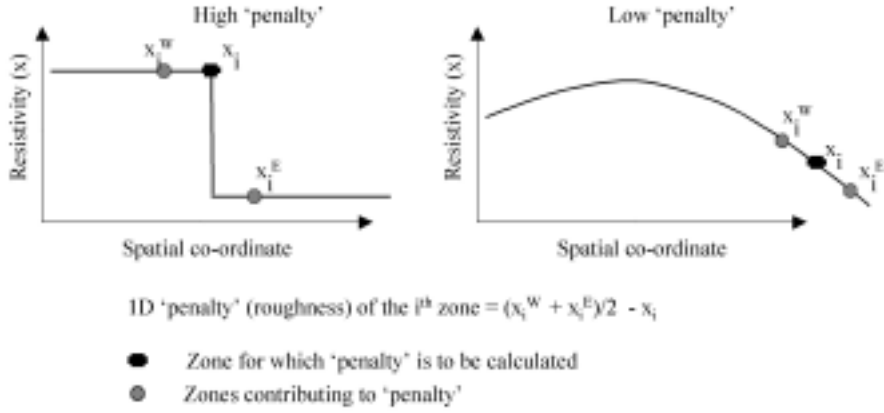
High 'penalty'
Low 'penalty'
Resistivity (x)
Spatial co-ordinate
1D 'penalty' (roughness) of the i^th zone = (x_i^W + x_i^E)/2 - x_i
Zone for which 'penalty' is to be calculated
Zones contributing to 'penalty'

Figure 24.8. 'Smoothness' constraints: penalties arising from smooth and abrupt spatial changes in the inverted resistivity model (based on Sasaki, 1994)

24.3 Constructing a constraint compatible with 'step' changes in resistivity

Considering likely subsurface conditions is a prerequisite to developing compatible constraints, the central idea being that the 'penalty' should be low for situations that are to be expected on the basis of the ground model developed from existing geological and geotechnical information. As illustrated in Figure 24.9, the resistivity of earth materials is highly variable and, when viewed globally, many lithologies can exhibit the same resistivity. These resistivity values are controlled by: porosity, pore-water saturation, pore-water resistivity, porosity style (e.g. cementation and particle shape) and matrix conduction (Archie, 1942; Brace and Orange, 1968; Grant and West, 1965; Keller and Frischknecht, 1966; Mualem and Friedman, 1991; Parkhomenko, 1967; Jackson et al., 1978). However, this is not normally the case within any one formation or sequence. A typical situation is shown in Figure 24.10 where the resistivity values can be seen to be diagnostic of sandstone and shale respectively. Furthermore, resistivity is used quantitatively as the primary property in the prediction of the fraction of pore space filled with water or oil (Archie, 1942).

A typical ground model might consist of various lithologies each exhibiting different ranges of resistivity values, modified by geological processes such as faulting and/or anthropogenic ones such as mining. A generic ground model typical of coalfields in western Europe exhibiting these attributes can be seen in Figure 24.11. The resistivity of coal is controlled by its ash content, high purity coal being characterised by values less than 10 ohm-m (Carmichael, 1982). Thus, coal provides a third lithology exhibiting a characteristic range of resistivity values, in addition to sandstone and shale. The resistivity of mine workings, such as those depicted in Figure 24.11, would be determined by their contents, normally either air or water, the resistivity of both being constant and readily assessed with a high degree of relative accuracy.

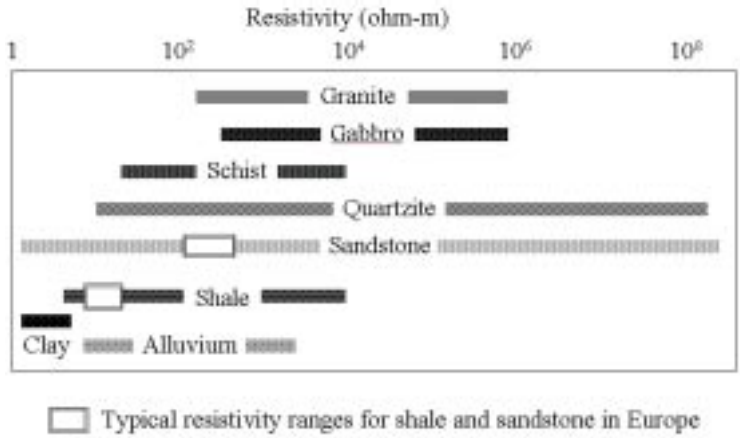

Figure 24.9. Ranges of resistivity values for shale and sandstone in Europe (based on Kearey and Brooks, 1984)

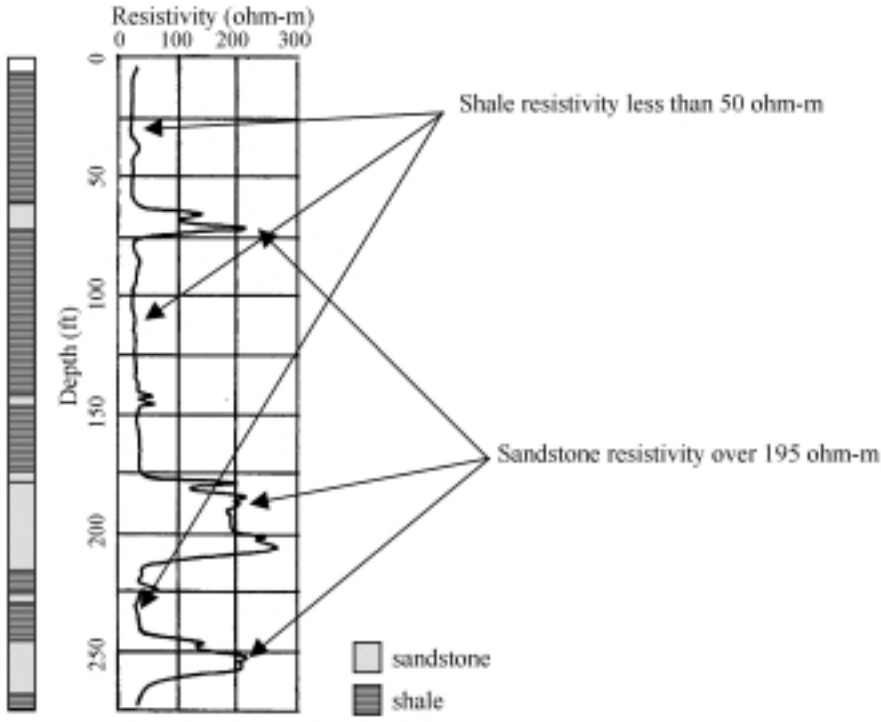

Figure 24.10. Typical field results in a sandstone-shale sequence, showing the ranges of resistivities changing abruptly between lithologies (based on Keller and Frischknecht, 1966)

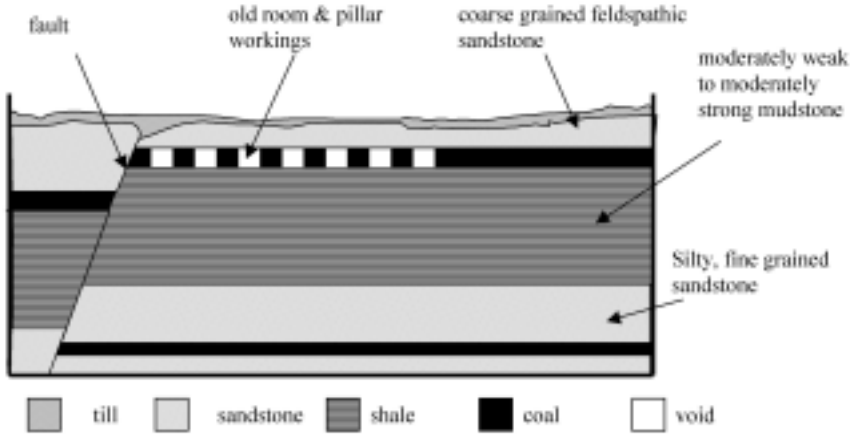

Figure 24.11. A geological model, typical of coalfields, showing sub-vertical faulting and sub-horizontal litho-stratigraphic boundaries that are to be expected (based on Fookes, 1997)

Consequently, even before a single 'field' measurement has been made, such a ground model tells us to expect abrupt lateral and vertical changes in the resistivity of the subsurface. For this situation, considering the philosophy of resistivity inversion described above, a compatible constraint would be one providing a low 'penalty' in the presence of abrupt spatial changes in the resistivity model. On this basis, the 'smoothness' constraint, providing high 'penalties' in this situation, is incompatible with such a ground model.

The 'smoothness' constraint has been modified to provide a low 'penalty' when the resistivity values of the inverted resistivity model are tightly grouped in a number of ranges. This 'grouping-by-value' utilises no spatial information whatsoever, creating larger 'penalties' as the span of the individual ranges of resistivity values increases, as shown in Figure 24.12.

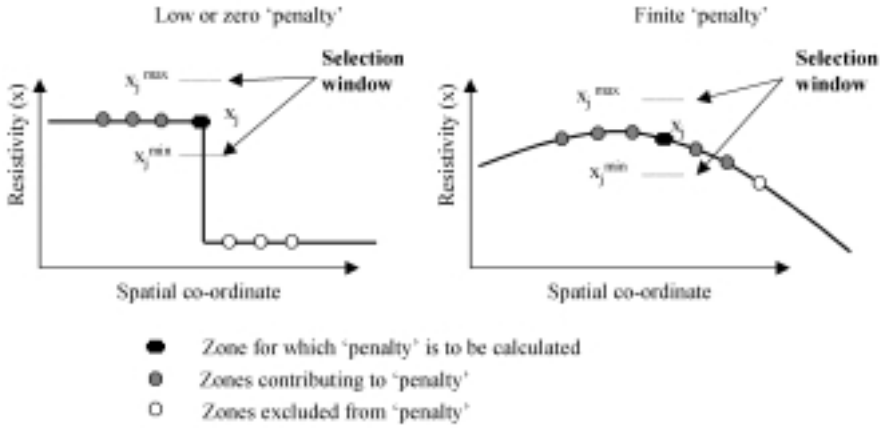

Figure 24.12. 'Grouped-by-value' constraint: the penalty for x_j is calculated following Figure 24.8, but using the zones of the inverted resistivity model having resistivity values within a pre-determined range about x_j, independent of location

The performance of 'smoothness' and 'grouped-by-value' constraints was tested using that portion of the inverted resistivity model in Figure 24.7 (lower) above a depth of -4.5 m and within X and Y intervals of 4 to 16 m and 2 to 10 m respectively. The test involved starting the inversion process from the 'true' resistivity model, the 'field' measurements being calculated from the 'true' resistivity model shown in Figure 24.6, this model incorporating both laterally and vertically abrupt changes in the values of resistivity. In common with the 'coalfield' ground model, these abrupt lateral and vertical changes in resistivity values lead us to expect the 'smoothness' constraint to be incompatible with the 'true' resistivity model.

The results in Figure 24.13 compare inverted resistivity models constrained both by 'smoothness' and 'grouped-by-value' with the 'true' resistivity model shown in Figure 24.6. The inverted resistivity model constrained by 'smoothness' (middle) can be seen to be the smoothest. However, it overshoots at the centre of the resistive body and undershoots immediately adjacent to it, resulting in errors of 50–100%; these results are similar to typical data seen in the literature, as discussed above. On the other hand, the inverted resistivity model constrained by

'grouping-by-value' is far closer to the 'true' resistivity model, the errors being seen in Figure 24.13 (lower) to be 10–15%. In summary, inverting using a constraint compatible with the ground-model improved the inverted resistivity model.

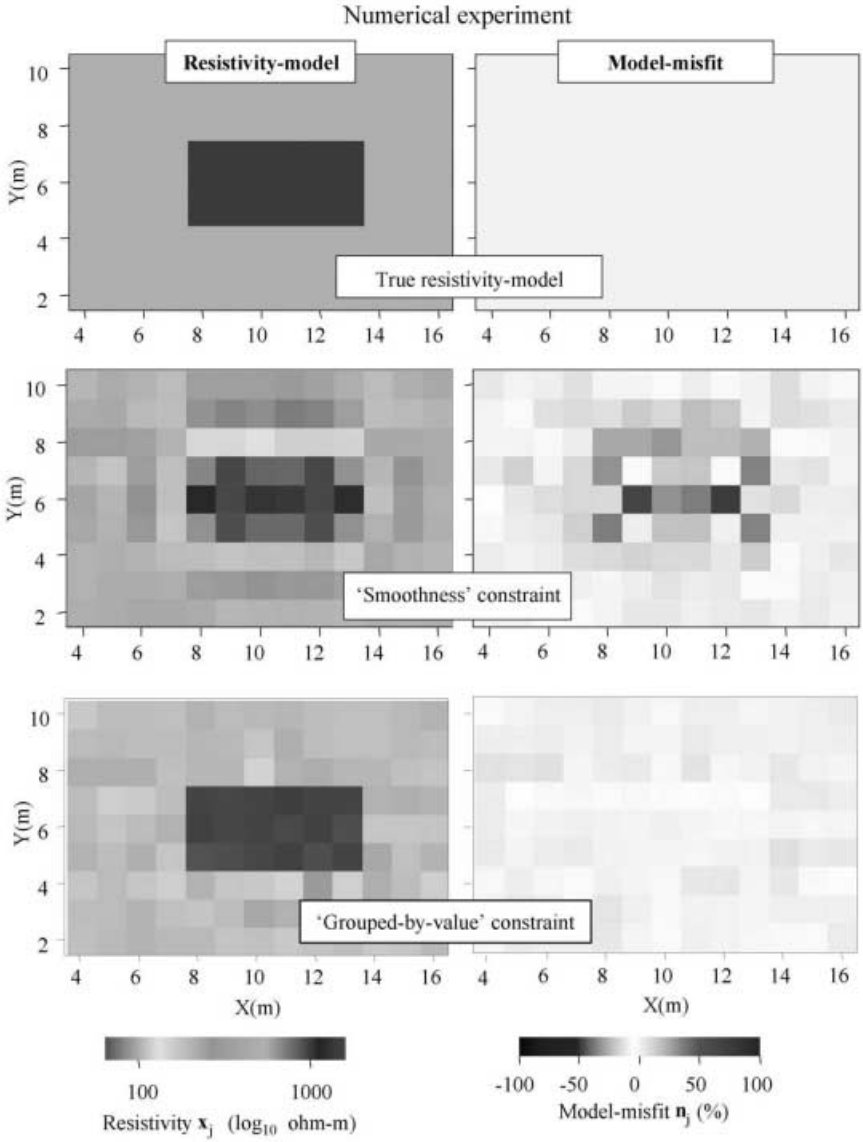

Figure 24.13. Display of the inverted resistivity model at a depth of z = -4.0 m, with testing constraints starting from the true resistivity model (after Jackson *et al.*, 2001)

24.4 A field case study

Resistivity models obtained by inverting measurements made over a faulted sandstone-shale sequence in the Saar coalfield are now described. On the basis of extensive trenching, the ground model (Figure 24.14) can be seen to be similar to the generic model in Figure 24.11 (Clasen, 1995). The location of a fault (Hanwiese) was identified at a site using ground probing radar (Greenwood *et al.*, 1994), where resistive arkosic sandstone was juxtaposed with conductive shale. The electrode array used in the field is the same as the one shown in Figure 24.6, comprising 12 current sources and 200 potential electrodes, resulting in a dataset of 4177 measurements and is described in greater detail elsewhere (Jackson et al., 2001).

The original inverted resistivity model obtained by applying the 'smoothness' constraint to the inversion can be seen on the left-hand side of Figure 24.15. Considering the depth range 2.5 to 3.5 m in Figure 24.15, a smooth transition in resistivity values can be seen across the fault; the corresponding ranges of resistivity values attributed to the sandstone and shale lithologies being 400 to 930 and 29 to 90 ohm-m respectively.

In contrast, the corresponding resistivity model obtained using the 'grouped-by-value' constraint includes an abrupt lateral change in resistivity across the fault in agreement with the distinct sandstone shale interface identified during trenching. The corresponding ranges of resistivity values for the sandstone and shale were far narrower, being 530 to 570 and 50 to 60 ohm-m respectively.

24.5 Conclusions

'Smoothness' constraints are the method of choice for inverting electrical resistivity measurements, but are often used without regard to whether the smoothness they impose on resistivity models can be justified in terms of subsurface conditions. Following a desk study to develop the ground model, a wealth of *a priori* information is normally available from which the range of possible subsurface resistivity distributions and their 'styles' may be deduced. Abrupt spatial changes in resistivity values are a 'style' of resistivity distribution commonly expected prior to surveying, for example.

For this style of resistivity distribution, a new 'grouped-by-value' constraint has been developed which produced a low 'penalty'. This in turn has resulted in significant improvements to the estimation of resistivity values and a reduction in spatial 'smearing' as illustrated by both numerical and field examples. Consequently, it is proposed that such constraints be used on the basis they produce low 'penalties' when applied to resistivity models having 'styles' compatible with the *a priori* ground model.

Acknowledgements

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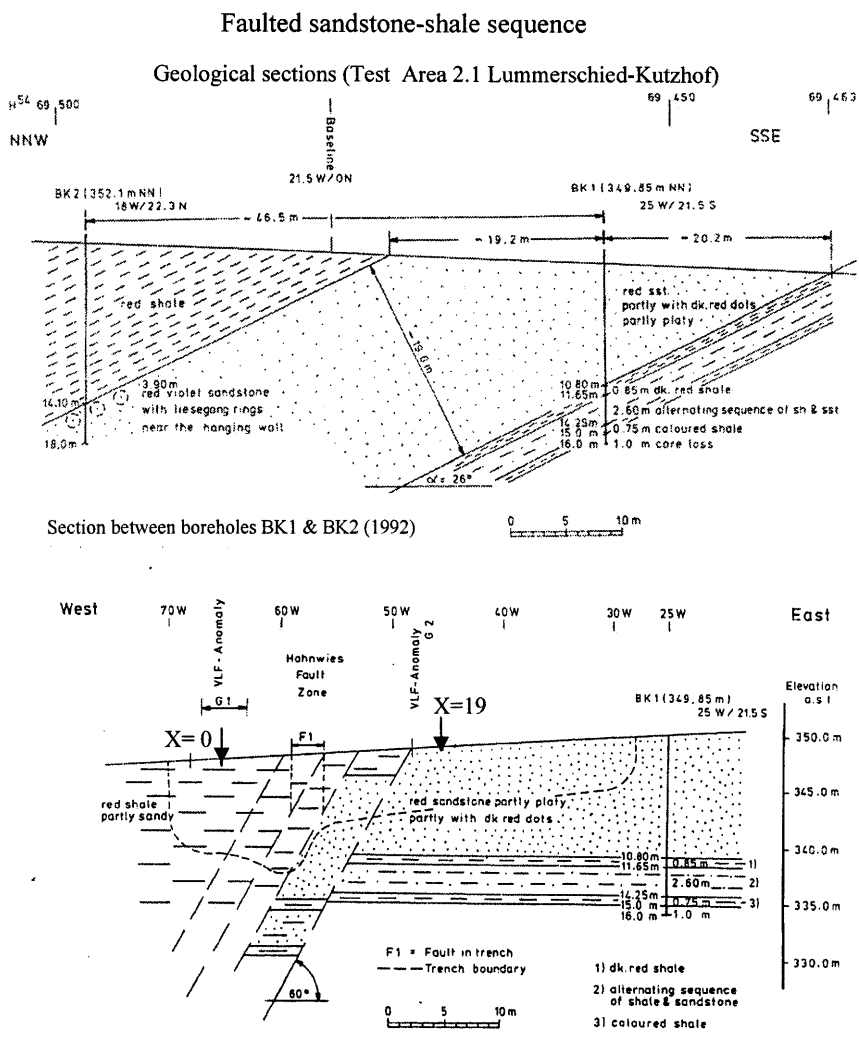

Figure 24.14. Testing two constraints by starting from the true resistivity model (after Clasen, 1995)

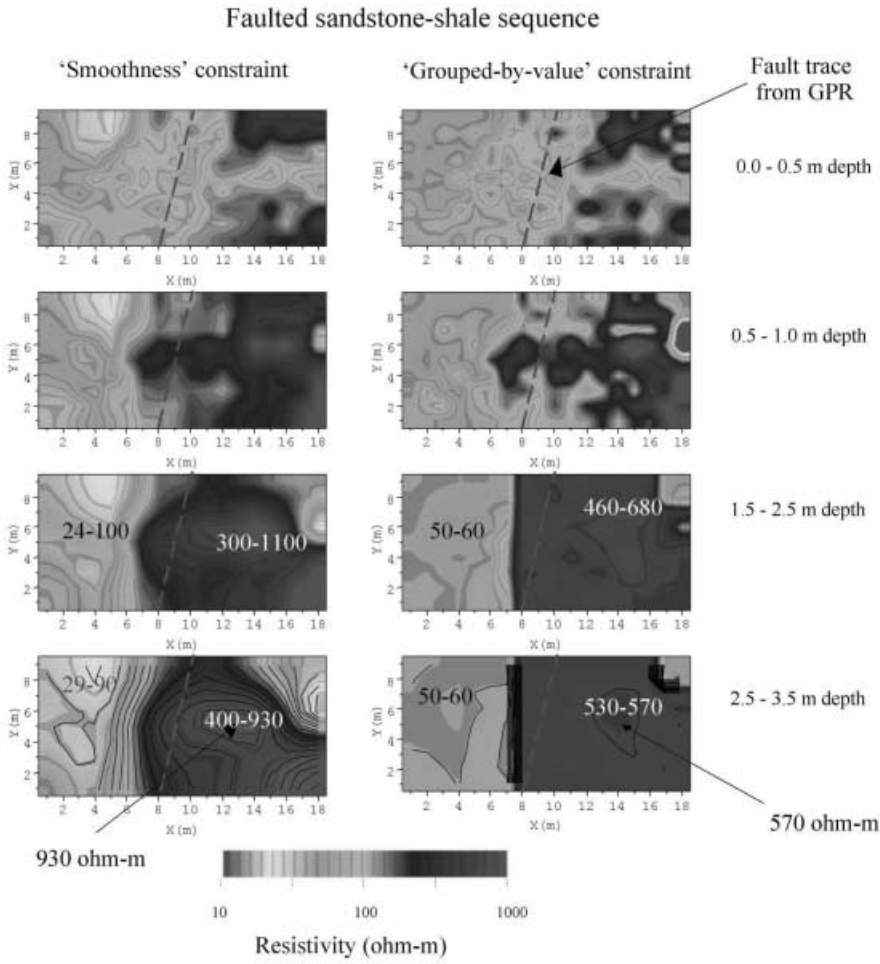

Figure 24.15. Inverting using the 'grouped-by-value' constraint resulting in approximately constant values of resistivity for the sandstones and shales in the depth range 2.5 to 3.5 m, in contrast to the results obtained using the 'smoothness' constraint (after Jackson *et al.*, 2001)

25 Characterisation of void space utilising pore network models

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25.1 Introduction

The micro-fabric of porous rocks influences a variety of transport processes of geological significance, for instance the contamination of groundwater. Transport coefficients (e.g. capillary pressure curves, absolute and relative permeability, hydrodynamic dispersion coefficients, formation factor and resistivity index) bridge the gap between pore-scale events and fluid transport at the macro-scale of a groundwater reservoir. These incorporate the microscopic dynamics within the macroscopic mass, momentum and energy balances (Celia et al., 1989; Hassanizadeh and Gray, 1993). Such coefficients are complex functions (Blunt et al., 1992; Ioannidis and Chatzis, 1993; Lowry and Miller, 1995; Tsakiroglou and Fleury, 1999), dimensionless flow rate parameters coupled with physicochemical properties of fluids (Avraam and Payatakes, 1995; Constantinides and Payatakes, 1996), wettability (Blunt, 1998) and saturation history (Dullien, 1992; Sahimi, 1995).

25.2 Pores

Optical microscopy in combination with image analysis techniques has been used for: (1) the determination of geometrical properties of 3D pore space by processing random sections with the aid of quantitative stereology (Underwood, 1970), and (2) the estimation of topological properties of the interconnected pore structure by analysing serial sections (DeHoff and Rhines, 1968; Lymberopoulos and Payatakes, 1992; Macdonald et al., 1986).

Mercury porosimetry is a fast technique for determining the capillary pressure curves. A methodology for characterising the pore structure of relatively macroporous materials has recently been developed and applied successfully to an outcrop of Grey-Vosgues sandstone (Tsakiroglou and Payatakes, 1997). The method combines data obtained from the serial sectioning analysis of porecasts with the

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analysis of experimental mercury porosimetry curves using a pore network simulator of mercury intrusion/retraction.

25.3 Fractures

Fractures are abundant in the ground and play an important role for the migration of fluids (D'Astous et al., 1989; Fredericia, 1990; Kueper and McWhorter, 1991).

One of the key parameters of a fracture is its aperture. This is defined as the distance between two opposite fracture surfaces. The bulk hydraulic conductivity of fractured media is related to the fracture aperture through a cubic law (Snow, 1969) that is based on a model of parallel fractures composed of vertical and smooth surfaces. Although this model is rarely representative of real fractures, it is commonly used in conjunction with hydraulic tests for calculating the 'hydraulic aperture' of fractured rocks and soils (Tsang, 1992; Witherspoon et al., 1980). More advanced methods using bulk flow data, breakthrough curves and entry pressures are also available for the calculation of fracture aperture (Hinsby et al., 1996; Sidle et al., 1998).

The true or 'mechanical aperture' must be measured directly on the fractured rock. Direct field measurements of realistic fracture aperture in soft sediments have not yet been performed. At the lab- scale, CAT-scanning images have been used to give rough estimates of the fracture apertures in granites and sandstones (Keller, 1998). Soft rocks tend to deform during sampling or measuring procedure and hence, the fractures must be sampled very carefully and stabilised before any measurement takes place. A typical methodology is the impregnation of the void space (fractures, macro-pores and matrix porosity) of samples with a resin (Gale, 1987; Gentier et al., 1989).

25.4 Characterising the micro-porous matrix of a clay till

Clay till is a fine-grained glacial sediment that is widespread in the Northern Hemisphere. In spite of the progress achieved on the macroscopic mapping of complex fracture systems in fine-grained sediments (Bosscher and Connel, 1988), and particularly in clay tills (Jakobsen and Klint, 1999; Klint and Gravesen, 1999), no effective systematic methodology has yet been developed for the characterisation of clay till single fractures, in terms of the geometrical and topological properties of their structure.

There is an apparent lack of integrated methods capable of determining the microscopic parameters of fractured porous media. In the present work, a methodology has been developed to determine the geometrical, topological and hydraulic properties of micro-porous matrices and single fractures encountered in clay till.

Intact samples were collected from three pits excavated on an abandoned tar factory (Ringe Site) situated in Funen island, Denmark (Sidle et al., 1998). The samples were impregnated with a polyester resin through a 'wet' procedure de-

scribed in detail in (Klint and Tsakiroglou, 2000) in order to avoid any undesirable disturbances of the initial structure. A small piece of the porecast (5 x 5 x 2 mm) was sliced and embedded in Araldite. Each new polished surface of the pore-cast was placed under an optical microscope, its image (picture) was taken with a video-camera, and was recorded on a videotape for further analysis (Figure 25.1).

For the determination of geometrical properties, the algorithm GETPO has been developed (Lymberopoulos and Payatakes, 1992) which reconstructs the 3D pore network from data of 2D pore features of serial sections (X,Y co-ordinates of two-dimensional pore sectionals). Here, the algorithm was used for the determination of the genus, which is a measure of the pore space connectivity (DeHoff and Rhines, 1968; Macdonald et al., 1986; Lymberopoulos and Payatakes, 1992), areal porosity and equivalent spherical diameter distribution of the 3D pore chambers (CSD). The CSD was derived from the equivalent circular diameter distribution of the 2D pore features, by using the Schwartz-Saltykov method of quantitative stereology (DeHoff and Rhines, 1968; Underwood, 1970). Each size distribution was fitted to a bimodal distribution function composed of two lognormal component distributions 1 and 2 by using the Marquardt method (Bard, 1974). The two porecasts were cut from a weathered and a non-weathered area of clay till.

The mercury intrusion curves of clay till samples were relatively broad towards both low and high pressures (Figure 25.2). This characteristic feature of capillary pressure curves is associated with: (1) a wide throat size distribution, (2) strong spatial pore size correlation, (3) high fractal roughness porosity and (4) low pore network connectivity (Tsakiroglou and Payatakes, 1998).

The shape of mercury intrusion curve shows that the breakthrough pressure (Drake and Ritter, 1945) is quite low and some of the pore volume may become accessible and filled with mercury through boundary pores having sizes larger than the upper size limit of mercury porosimetry (D_{max}~150•m). Therefore, mercury porosimetry may underestimate the porosity of macroporous materials such as the investigated clay till samples. For this reason, the porosity was considered as equal to the average areal porosity that was determined by image analysis of serial sections.

The throat-diameter distribution (TSD) (Figure 25.3a) and the ratio of fractal to total porosity were estimated iteratively by comparing the simulated with the experimental mercury intrusion curve (Figure 25.3b). After each simulation, the absolute permeability, k, of the pore network was calculated by using an electrical analogue of the pore network and solving a system of coupled linear equations (Tsakiroglou and Fleury, 1999). After eight iterations, the experimental mercury intrusion curve could be predicted satisfactorily.

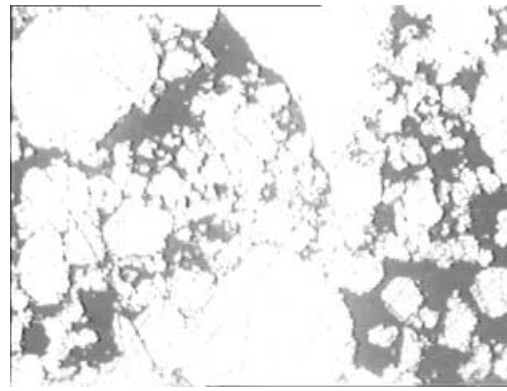

Figure 25.1. Section photograph of sample ct-3b (total area =1655•m x 1240•m)

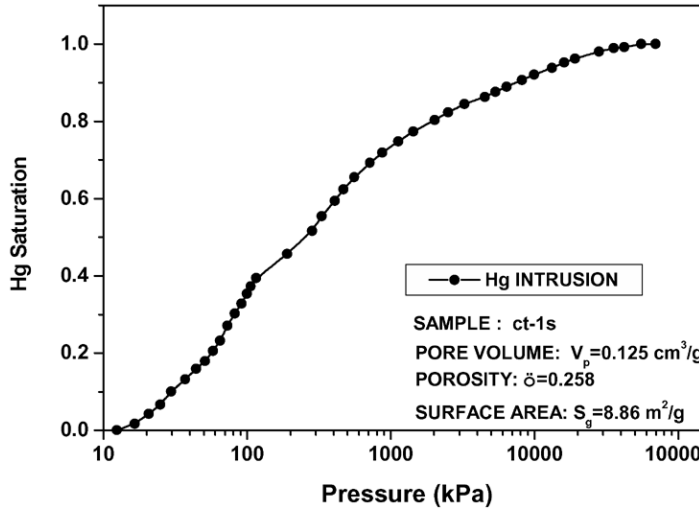

Figure 25.2. Experimental mercury porosimetry curve of clay till (sample ct-1s)

25.5 SEM image analysis

Optical studies of SEM images revealed (Klint and Tsakiroglou, 2000) that the aperture of clay till fractures resemble an interconnected irregular network of channels (Figure 25.4) rather than the void space left between two smooth parallel plates. A representative model of the aperture of clay till fractures is a network of elliptical channels of equal length (Figure 25.5).

SEM image analysis was used to characterise the fracture aperture in terms of the geometrical parameters of 2D networks of elliptical channels of equal length.

Thick sections of resin impregnated clay till fractured samples were prepared and photographed in visible incident and UV light for identifying fractures and characteristic clasts on the sample surface.

Features belonging to the same fracture were identified and digitised (Figure 25.6) and the following parameters were measured: (1) the major axis length, defined by the two border pixels that are the farthest apart; (2) the minor axis length, drawn by two border pixels defining the longest line perpendicular to the major axis; (3) the X,Y co-ordinates of the binary centre of mass of each feature (geometric centre), calculated by averaging the pixel co-ordinates over the entire feature.

Once all measurements had been performed, the statistical distribution functions of major and minor axis length were determined. The distances between geometric centres of adjacent features were determined and averaged over the entire section to calculate the mean distance between fracture features which was considered as an approximate estimate of the mean channel length <h> (Underwood, 1970). The dimensions of the elliptical channels of the 2D network model were considered equal to the measured lengths of major and minor axes of the 2D features respectively.

25.6 Conclusions

The microscopic pore space properties of the ground can be quantified in terms of pore network models by combining digitised images of serial sections with algorithms of 3D reconstruction, and mercury porosimetry data with deterministic simulators of mercury intrusion/retraction in chamber-and-throat networks.

High connectivity, bimodal throat (TSD) and chamber (CSD) diameter distributions, strong spatial chamber-to-throat size correlation and intermediate values of the surface roughness fractal dimension and porosity were found for the matrix porosity of clay till samples.

The analysis of SEM images allowed quantification of the aperture of single fractures in terms of networks of elliptical channels, whereas reliable estimates of the hydraulic properties of fractures can be obtained with the use of effective medium approximation (EMA).

Broad distributions of the minor and major channel axis lengths, strong spatial correlation of major to minor axis length, and absolute permeability differing significantly from that predicted by the cubic law were found for the clay till fractures studied.

Critical path analysis offers promise for deriving closed relationships, allowing estimation of the absolute permeability of fractures from electrical measurements and microscopic properties of the channel network.

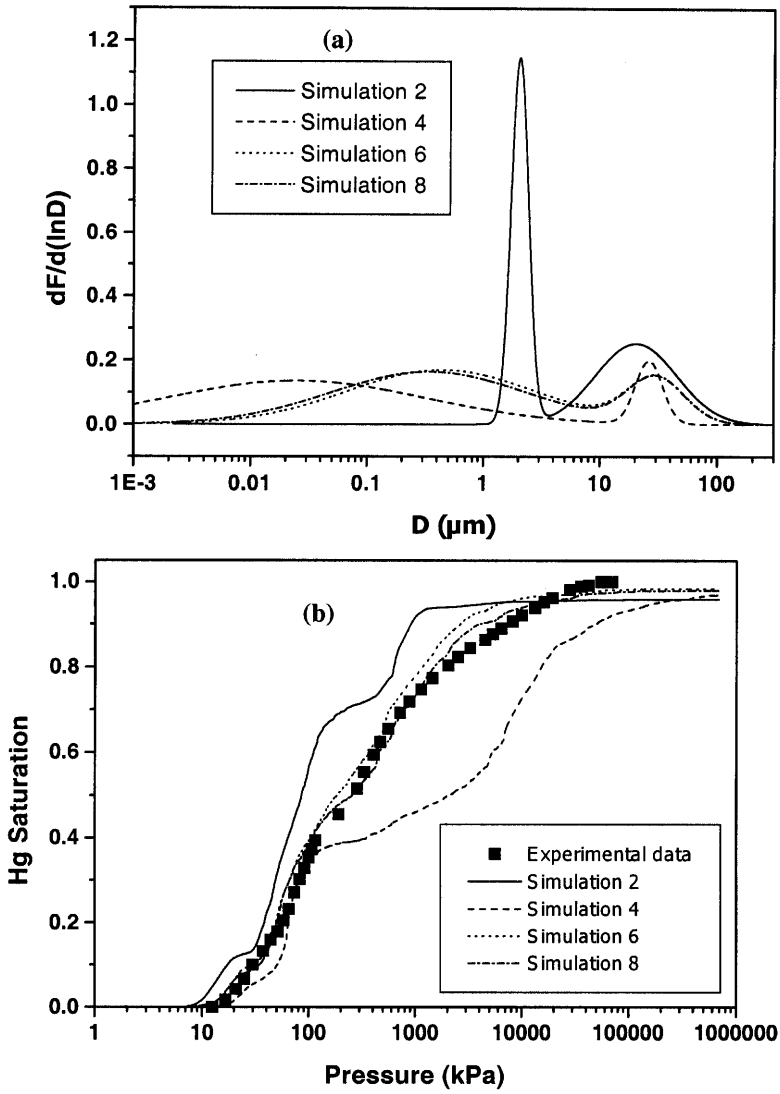

Figure 25.3. **(a)** Estimates of the throat diameter distribution from several iterative simulations, **(b)** Comparison of the simulated mercury intrusion curves with the experimental curve in Figure 25.2

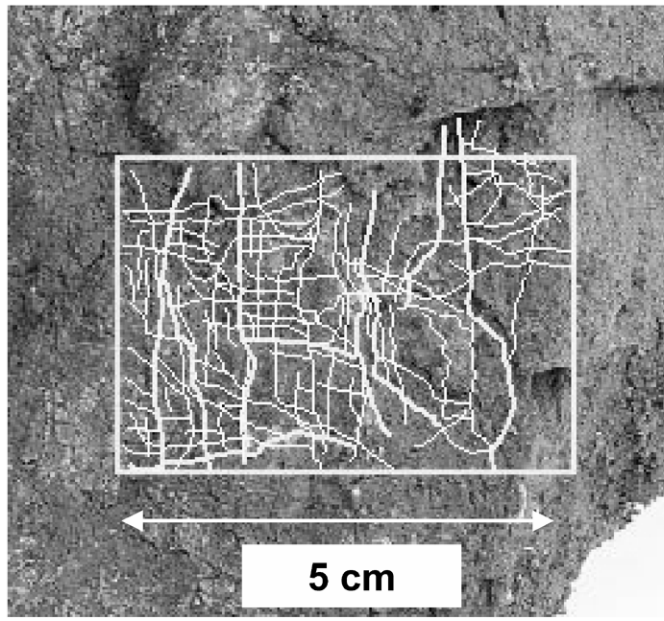

Figure 25.4. Identification of the channel network skeleton (white) and rootholes (yellow) on a transverse section of clay till fracture

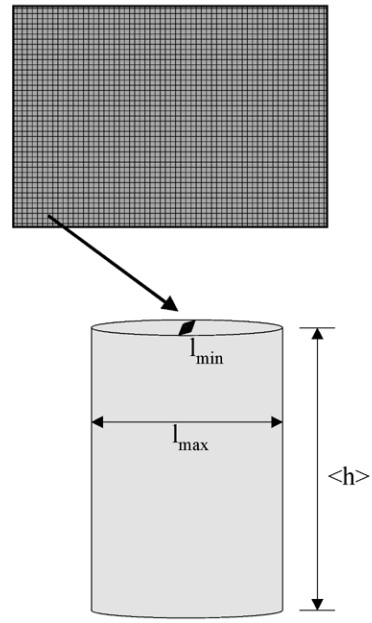

Figure 25.5. Aperture model for a fracture in clay till

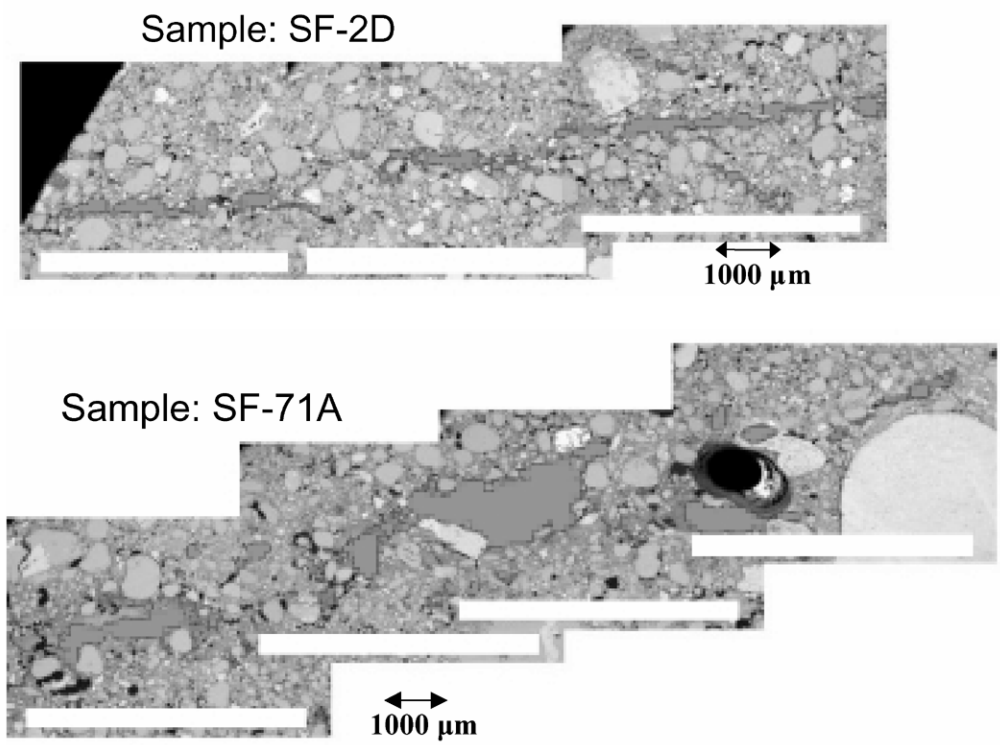

Figure 25.6. Digitised SEM images of a fracture in clay till

Acknowledgements

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26 Assisting data interpretation: the cone penetration test

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26.1 Introduction

The construction of a subsurface model requires considerable expert knowledge, tends to be labour intensive, and may have a significant degree of data redundancy, especially for very large projects.

Every year in the Netherlands, about 30,000 Cone Penetration Tests (CPTs) are performed, yet just 5,000 boreholes are sunk. Consequently, many Dutch institutions and companies have compiled extensive databases of CPT results. However, due to the time involved in analysing these data, much is left unused. A more reliable impression of the subsurface could result if such CPT data could be incorporated in later ground characterisation studies.

26.2 The INURCS project

The aim has been to explore the possibility of using soft computing tools to assist subsurface modelling with CPT data. The intention has been to use as much available CPT data as possible, yet be objective and take cogniscance of uncertainty.

The techniques have been developed as part of the INURCS project ("Indelingssystematiek van de Nuenen Groep in Roerdal / Centrale Slenk"), a cooperative venture between TNO-NITG (Netherlands Institute of Applied Geotechnics) and Utrecht University. One of the goals has been to develop a geological model for the upper 30 metres of the subsurface in the Roer Valley Graben area in the southern part of the Netherlands (Figure 26.1).

The Roer Valley Graben is a continuously subsiding tectonic basin, within which new sedimentation can take place. Sediments of aeolian, lacustrine and fluvial provenance environments are known, dating from the Middle Pleistocene. Periglacial processes have subsequently disturbed the sediments. As a result, considerable spatial and temporal variations in sedimentary character occur (Schokker, 2001).

For this study, 75 new CPTs were conducted (Figure 26.1); the cone resistance (q_c) and the friction ratio (R_f) were measured every 20 mm.

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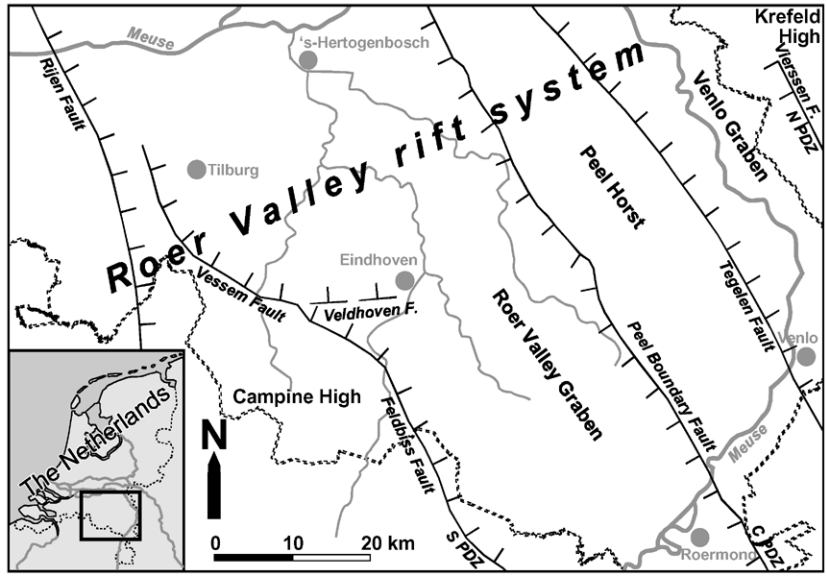

Figure 26.1. Map of the study area. The CPTs were conducted along a line marked by the text "Roer Valley rift system"

26.3 CPT interpretation

The need to analyse many CPT results in a consistent manner led to the need to develop an automated process to assist interpretation. This would need spatial knowledge concerning the distribution of relevant parameters and knowledge of the geological profile.

The approach has been used to automatically segment the CPT sequence using a dynamic programming algorithm proposed by Huijzer (1992), discussed further below. The next step is to parameterise the segment signals, a pre-processing step for fuzzy clustering.

26.4 Automated segmentation of CPT sequences

Huijzer's dynamic programming algorithm is based on constrained hierarchical clustering; a 'cluster' is a sequential series of CPT observations. All possible segmentations of a CPT trace are evaluated and the segmentation that minimises the pooled within-group dispersion is identified as being the optimum ('correct') segmentation.

If the segments are denoted by g and n_i is the observation at the boundary between two segments, the pooled within-group dispersion matrix is given by (Huijzer, 1992):

$$\mathbf{W} = \sum_{i=1}^{g} \sum_{j=n_{i-1}+1}^{n_i} \left(\mathbf{X}_j - \overline{\mathbf{X}}_{n_{i-1},n_i}\right)\left(\mathbf{X}_j - \overline{\mathbf{X}}_{n_{i-1},n_i}\right)' \tag{1}$$

$$\overline{\mathbf{X}}_{n_{i-1},n_i} = \sum_{j=n_{i-1}+1}^{n_i} \frac{\mathbf{X}_j}{(n_i - n_{i-1})} \tag{2}$$

One of the input parameters for this method is the number of segments in the CPT sequence. In most geotechnical investigations, this number will not initially be known. Huijzer (1992) examined several statistical criteria which might be used to determine the number of segments, but found that the results were not geologically relevant.

Another approach considered by Huijzer (1992) was to use a fixed number of segments based on the length of the CPT. The risk of such an approach would be that not all the relevant features would be extracted since a relatively short CPT may well contain relatively few relevant features.

In the absence of a good statistical method to determine the number of segments in a CPT, a measure based on the CPT length was considered. For the regional survey in the Roer Valley, an average of 1 cluster per 2 metres CPT length was chosen, based on the geologist's expert knowledge. In order to select the most important features, the CPT sequences were then segmented between 2 and 40 each. The most frequently occurring boundaries within each partition levels were then selected.

As the vertical size of the extracted feature tends to get smaller with increasing partition level, such a method ensures that all major features, large and small, are selected. This approach worked well, as can be seen in Figures 26.2 and 26.3. Figure 26.2 is akin to how a human expert would segment the sequence Figure 26.3 shows the best segmentation for 24 segments from a statistical viewpoint.

The choice of the amount of segments per metre down the CPT depends on the purpose of the CPT investigation and the variability of the geological profile. An average of 1 segment per 2 metres CPT length proved to be a good choice for the purpose of a regional facies analysis for the Roer Valley.

26.5 Segment parameters

Once the CPT sequences have been segmented, the resulting segmentation needs to be characterised in such a way that comparison with other segments is possible. This parameterisation is a pre-processing step for the fuzzy clustering procedure which follows.

A logical approach is to use measures of central tendency: the median of the q_c and R_f data together with the (relative) interquartile range. The median and range, although useful, are not the only characteristics which a human interpreter would use to compare CPT segments. Some lithological aspects of the subsurface can also be related to the shape of the CPT trace.

Coerts (1996) developed other parameters in order to quantify such shapes. These parameters measure the trend of the signal, the concavity of the signal, the number of fluctuations about the median and the number of significant peaks. Coerts also described a 'sharpness of boundary' coefficient, but this parameter was later found not to be helpful to the analysis of fuzzy clustering.

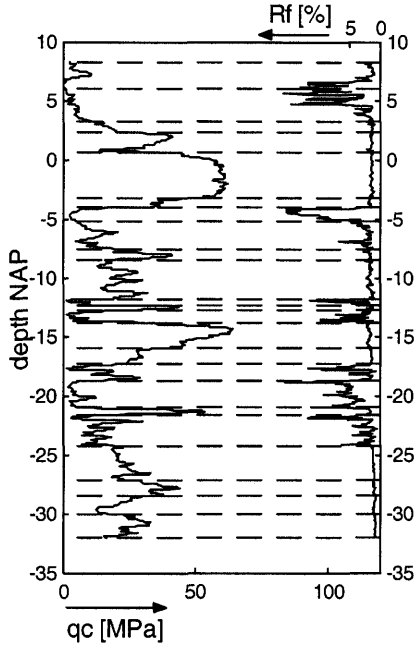

Figure 26.2. Segmentation of the sequence for CPT M39: 24 boundaries were selected from 2 to 40 segment partitions

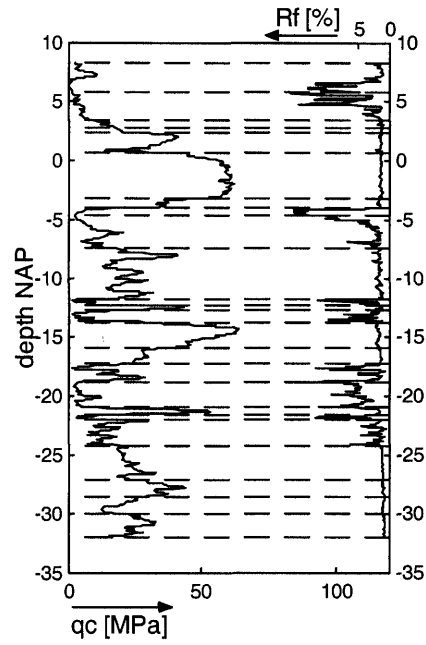

Figure 26.3. Segmentation of the sequence for CPT M39: 24 boundaries were selected from just the 24 segment partition

26.6 Fuzzy clustering

Having segmented the CPT sequence using Huijzer's algorithm and parameterised it, the next stage was to spatially correlate the CPT segments. This has been done using the fuzzy c-means algorithm and an extension of this, the E-FCM algorithm.

26.6.1 Traditional fuzzy c-means

The fuzzy c-means algorithm (Bezdek, 1973; Hoppner, 1999) is the best-known fuzzy clustering algorithm. There are two problems that have to be solved when performing a fuzzy c-means analysis. One problem is to find the value of c, the number of clusters present in the data set. The other problem concerns the pre-processing of the data.

Many measures of cluster validity have been developed to find the optimum number of clusters in a dataset (Bezdek, 1997). Neither the Partition Entropy and Partition Coefficient (Bezdek, 1981) were able to identify more than two clusters no matter which type of pre-processing was done. This is too little for a geotechnical application. In the Roer Valley project, the best results were obtained using the Xie-Beni Separation index (Xie, 1991) and the Roubens' Fuzziness Index (Roubens, 1982). These validity measures both found six clusters in the dataset.

Because of the differences in the units of the parameters, it seemed logical to conduct a pre-processing step prior to the fuzzy c-means analysis. Without pre-processing, the algorithm considers parameters with higher standard deviations to be 'more important' than parameters with lower standard deviations. Normalisation of the parameters removes this effect but, in CPT data analysis, the effect is actually desirable. Segments with a low cone resistance and high friction ratio should not belong to the same geotechnical cluster as a segment with a high cone resistance and a low friction ration, no matter how much the trend and the concavity of the traces may look alike.

The standard deviation of the m_{qc} values is larger than the standard deviations of the group of m_{Rf}, p and r values. The standard deviations of i,ri , t and c values are the smallest and therefore carry the least weight in the fuzzy cluster analysis. The result of running the cluster analysis for the 6 clusters found by the cluster validity measures discussed earlier is depicted in Figure 26.4, and found to be satisfactory. The marker layer in this section, the light grey (clay) layer, is clustered correctly. The clustering result of the other segments also seems reasonable.

26.6.2 Extended fuzzy c-means ('E-FCM')

The standard fuzzy c-means algorithm has several drawbacks. Because it tends to iterate towards local minima, a good initialisation is required to arrive at a global minimum. Especially when there are clusters with varying data density and with different volumes, as will be usually the case with geotechnical data, a bad initialisation can easily lead to sub-optimal clustering results.

Also, user supervision is desirable to ensure that the correct number of clusters is chosen. Bezdek *et al.* (1997) revealeds no single 'ultimate' cluster measure.

To overcome these difficulties, an algorithm was implemented that uses volume prototypes instead of point prototypes ('cluster centre points') and unsupervised similarity-based cluster merging. This Extended Fuzzy c-means (E-FCM) algorithm was developed by Kaymak *et al.* (2000).

The volume of the prototype is changed dynamically to best fit the data. Thus a dense spot of data points can fall inside a prototype and be fully assigned to a sin-

gle cluster. The prototypes will not be 'pulled' towards each other because of the partial memberships of the data points. This improves the quality of the clustering process, as shown by Kaymak *et al.* (2000).

The cluster initialisation problem is addressed by a similarity-based cluster merging approach. The algorithm is initialised with a sufficient number of clusters. Then the most similar clusters are merged. The process is repeated until the similarity between the clusters is lower than a certain threshold. This not only deals with the initialisation problem, but also determines the number of clusters dynamically and in an unsupervised way, whilst reducing the computing power required.

When the E-FCM algorithm was run on the CPT data, 3 clusters were found, primarily on the basis of the median of the cone resistance. Visual inspection of these clusters showed that the result was logical from a geotechnical viewpoint: the three clusters distinguished loose soils (peat and silty sand), moderately dense sands, and dense sands (see Figure 26.5).

The influence of the median of the cone resistance parameter on the clustering is reduced. When the algorithm is run again on these three datasets, a total number of eight sub-clusters were retrieved (Figure 26.6).

Because of the heterogeneous ground and the comparatively large CPT spacing (500 metres), the validity of the clustering is not immediately evident. Nevertheless, the clustering seems reasonable. A few marker layers occur and the two-step E-FCM approach identified them correctly; one is indicated in Figure 26.6.

The results of the E-FCM analysis are comparable to the established fuzzy c-means analysis using the Xie-Beni cluster validity measure. However, the E-FCM algorithm is faster, unsupervised, and theoretically more robust.

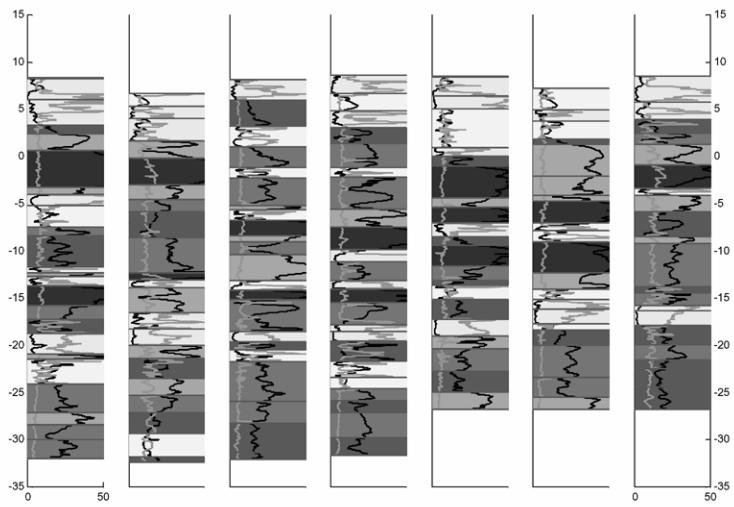

Figure 26.4. Result of fuzzy 6-means clustering of CPT segments from CPTs M39 to M45, described by 12 parameters. In light grey (at -20 m depth) is a marker layer which was correctly classified

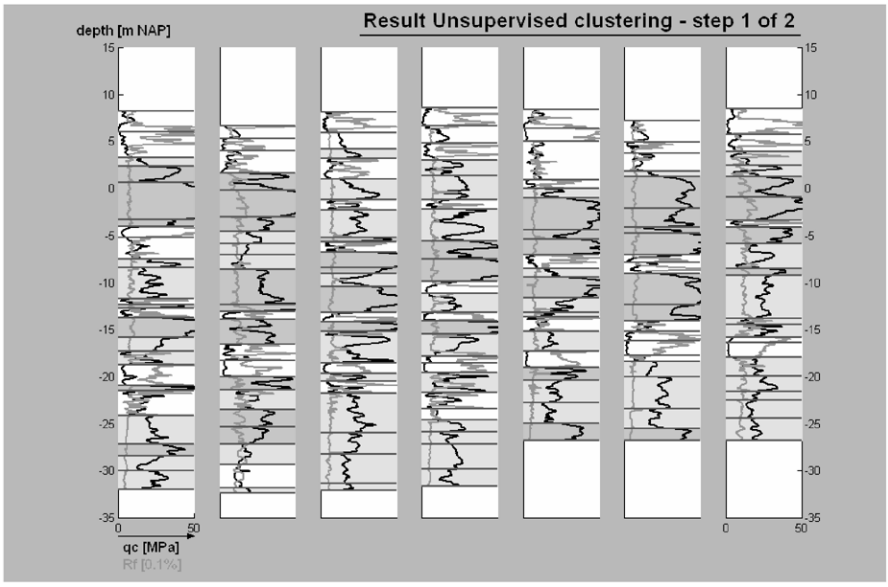

Figure 26.5. Result of runing the E-FCM algorithm on the CPT data, showing three clusters

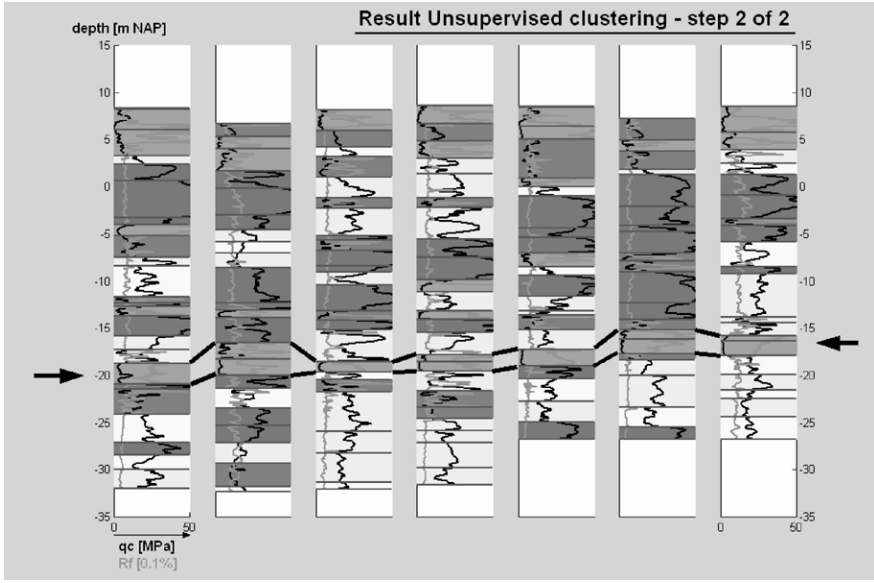

Figure 26.6. Running the E-FCM algorithm on data for three clusters, resulting in eight sub-clusters. Between the arrows lies one of the marker layers that had been correctly classified (*c.f.* Figure 26.4)

26.7 Conclusions

Although the two-step E-FCM algorithm does not on its own constitute a 2D subsurface model, the results are sufficiently encouraging to conclude that geotechnically useful semi-automated subsurface modelling of CPT data is feasible. The usefulness of the results will be highly dependant on the heterogeneity of the ground profile and the scale of the CPT investigation programme.

The method is fast; the CPT dataset is large, yet can be processed within a day on a PC. Although the method has yet to be fully optimised, it offers considerable promise at reducing the time needed to model the ground during a large site investigation project.

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Part F Managing Uncertainty

There is increasing pressure on organisations to not only provide basic data and information, but also to explicitly package and disseminate knowledge for use by society with informed decision-making. The result is an increased demand for user-specific solutions that contain a clearly documented level of uncertainty. Further, society requires that the geoscience community offer expert insight to guide them in making judgements about future risks and consequences.

The tenet "No data – no gain" highlights the importance of high quality, well managed data. This also includes aspects such as the integrity of source data (especially that from external sources) and reproducibility of observations. It is considered that two major processes support modelling: data management and metadata. It is essential that these are put in place.

Uncertainty within historical data can be catered for by using stochastic simulation, the basis for which is statistical information observed at outcrop and neighbouring sites; stochastic generators are then used.

Existing geoscientific investigations generally are not adequately capturing the pertinent data, and so inhibiting the formal process of knowledge and wisdom creation. The process and predictive models developed by geoscientists are the knowledge-based requirements of 'decision analysis'. These models include sensitivity, uncertainty, and predictive analysis, provided in a probabilistic framework.

As predictions require increasingly precise statements of error and bias, the limitation of models as summaries of possible ground states becomes increasingly evident. Models are not the reality. Nevertheless, effective visualisation leads people to suspect that they may be seeing reality. Thus a number of different kinds of uncertainty are becoming apparent: conceptual, numerical and observational (data *per se*).

While the goal of many geoscientists and their organisations remains to provide relevant 'decision information' capable of supporting the decision analysis process, they are limited by their incomplete understanding of that process.

D'Agnese and O'Brien (*this volume*) explain that "A geoscience information infrastructure is needed to facilitate the dynamic, bi-directional flow of data, information, and knowledge. This 'GeoInfrastructure' is constructed upon the technological hardware and software of the information age and so includes advanced analytical and visualisation tools fully supported by databases, data warehouses, and data-management systems. It also requires technological advancements in the development and adaptation of data, information, and knowledge models to provide better structuring of data, information, and knowledge during geoscience investigations."

The emerging field of geoinformatics provides a vehicle for creating the desired 'GeoInfrastructure' and so doing it enables geoscience-knowledge integration.

Implementation of such a geoscience knowledge integration paradigm will require organisations and the geoscience community to develop protocols for knowledge integration that enable growth in data management maturity, in order

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that the full potential of integrated data management can be realised. The 'GeoInfrastructure' will tie the protocols together and facilitate increased data-management maturity.

This volume has emphasised the utility of maturing information collection, analysis, and processing technologies to distinct application areas. In the final chapter, Turner and Rosenbaum in the final chapter propose a research agenda and the formation of European and international research networks, together with one or more centres to provide the critical mass needed to realise the full potential of co-operation, synthesis, integration, and innovation.

The Spa conference is merely the latest in a series of meetings to consider these issues. Ideas concerning the development of a Global Geoscientific Knowledge Network are presented, pointing the way towards overcoming some of the impediments to subsurface characterisation. Establishing such a network offers considerable advantages, the most important being:

- Many societal issues transcend political boundaries; thus, mandating facilitation of data sharing;
- Common protocols enlarge the "customer base" for the geoscientific community and make the "geoscience business market" more attractive to commercial software providers;
- A more closely aligned geoscientific community results in a more efficient, societally relevant, and marketable geoscientific knowledge-base.

Such ideas were also recently raised at another Euroconference sponsored by the European Science Foundation (ESF) and the European Union (EU), entitled "Geovisualisation", held at Albufiera, Portugal, 9–14 March 2002. Their conclusions closely parallel those at Spa the previous year. For example, they state that the primary purpose of geovisualisation is to provide *insight*. They conclude that visual geospatial displays can help explore data, create hypotheses, solve problems, and create and disseminate knowledge – leading to discovery, explanation, and understanding of natural or socio-economic processes, and such understandings can support decision-making.

27 Impact of geoinformatics on the emerging Geoscience Knowledge Integration Paradigm

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27.1 Introduction

The advent of computers has provided valuable tools for the geoscience community to use in addressing societal concerns. Geoscientists have become accustomed to using vast data and information bases to conduct complex analyses. For the last twenty years, numerous investigations have implemented and evaluated various techniques for integrating data and information. However, the full potential of data, information, and knowledge integration has not yet been realised.

As the geoscience community moves into the 21st century, there will be a clear paradigm shift regarding how geoscientists do their work and interact with each other. In the future, geoscientific investigations will shift from a more passive role of data analysis and information management to a more active role that seeks to create, integrate, and transfer knowledge in ways that are responsive to social, political, and economic needs.

The emerging discipline of "Geoinformatics" provides the appropriate base for such integration. Geoinformatics address the growing need for utilising multidisciplinary geoscience data to understand complex Earth systems. Applying the geoinformatics concept demands a new paradigm that includes not only the more traditional technological issues of geoscience data collection, storage, retrieval, and processing, but also new tasks. These include the formulation of essential data, information, and knowledge models, the formalisation of "best-practice" workflows, and ultimately the application of knowledge management and decision support.

This "Geoscience Knowledge Integration Paradigm" is a practical extension of the data and information integration achievements of the late 20th century. This paradigm is a prerequisite for augmenting our ability to develop and deliver timely and cost-effective solutions to societal concerns. The full implementation of this paradigm will ultimately require the geoscience community to realign organisational structures.

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27.2 Addressing society's emerging concerns

The Geoscience Knowledge Integration Paradigm is emerging at a time when many within the geoscience community realise that their historical and accustomed role of providing data and information is no longer sufficient, because society is now demanding knowledge and wisdom.

Realignment and integration of geoscience research and applications to more effectively address society's emerging concerns is an important discussion topic within many public geoscience organisations. The following excerpts are but a small sample of these discussions and recommendations:

- "In the future, information (and knowledge) management at the USGS should shift from a more passive role of study and analysis to one that seeks to convey information (and knowledge) actively in ways that are responsive to social, political, and economic needs." (National Research Council, 2001)
- "The challenges and opportunities ahead will demand closer relationships between the British Geological Survey and all of its stakeholders." (Natural Environment Research Council, 1999)
- "Without mastering geoscientific knowledge management, geoscientific research would remain on a relative low grade of 'information processing'." (Netherlands Institute of Applied Geoscience TNO-NITG Annual Report, 2000)

These discussions emphasise the evolution of these organisations from agencies that are organised predominantly to make discoveries, and convey to society what they have discovered, to agencies that are organised to understand how the earth works and convey to society how best to cope with the realities of interacting with the Earth (NRC, 2001).

There is increasing pressure on these organisations to not only provide basic data and information, but also to explicitly package and disseminate knowledge for use by society with informed decision-making. The result is an increased demand for user-specific solutions that contain a clearly documented level of uncertainty. Solutions connected with explicit levels of uncertainty may be used by society to make operational decisions. Further, society requires that the geoscience community offer expert insight to guide them in making judgements about future risks and consequences (Konikow and Bredehoeft, 1992).

27.3 From data to wisdom

The geoscience community integrates basic data and applies scientific expertise to provide knowledge and wisdom. The relationships and characteristics of data, information, knowledge, and wisdom are summarised in Table 27.1. Existing data-management methods do not readily support this progression from data acquisition

to scientific information and then to knowledge and, ultimately, to scientific wisdom by geoscientists.

Table 27.1. Definition of basic terminology

Term	Definition
Data	Simply structured records of transactions
Information	Adding meaning and context to data with the intent of influencing the perception of a receiver
Knowledge	A fluid mix of experience and contextual information that provides a framework for evaluating and incorporating new experience and information
Wisdom	Enabling wise decision-making by applying knowledge, values, and expert insight

The integrating progression from data to wisdom can be illustrated through the use of a pyramid (Figure 27.1). Data and information form the foundation of the process and are maintained by, and contained within, the geographical information systems, technical databases, warehouses, and archives of an organisation or community. For example, geoscientists develop a geological framework, which is a conceptual model of the observed system, using acquired data, information, and their understanding of natural processes. Currently, this process is conducted using workflows developed by individuals involved with a specific study. The geological framework may be subsequently abstracted into process and/or predictive models that provide a better understanding of the natural phenomenon that is being observed. Such understanding produces knowledge and this knowledge, when further managed and applied to provide insight for societal decision-making, is manifested as wisdom.

Existing geoscientific investigations generally do not adequately capture or enable the formal process of knowledge and wisdom creation. The process and predictive models developed by geoscientists are the knowledge-based requirements of 'decision analysis'. These models include sensitivity, uncertainty, and predictive analyses that are provided in a probabilistic framework. Such analyses provide a basis for wise decision-making (TNO-NITG, 2000). While the goal of many geoscientists and geoscience organisations is to provide relevant 'decision information' that can support the decision analysis process, they are limited by their incomplete understanding of the decision process (Turner, *this volume*).

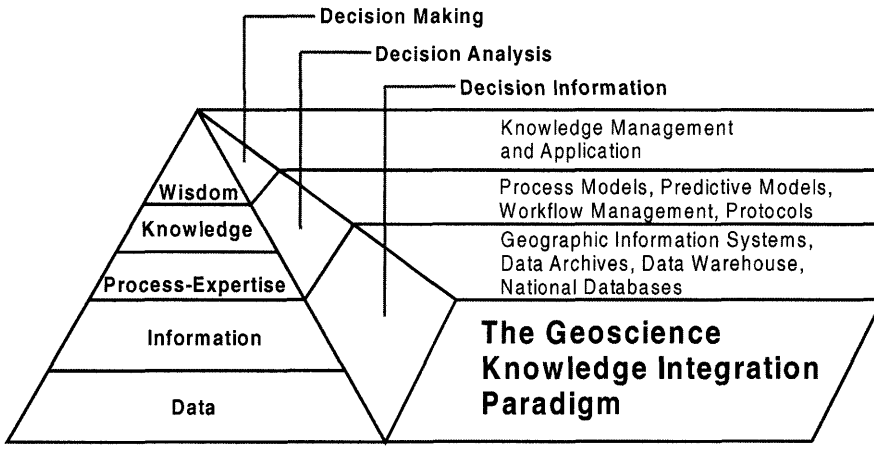

Figure 27.1. The Geoscience Knowledge Integration Paradigm (modified from TNO-NITG, 2000)

27.4 The need for a GeoInfrastructure

A geoscience information infrastructure is needed to facilitate the dynamic, bi-directional flow of data, information, and knowledge. This 'GeoInfrastructure' is constructed upon the technological hardware and software of the information age and so includes advanced analytical and visualisation tools fully supported by databases, data warehouses, and data-management systems. It also requires technological advancements in the development and adaptation of data, information, and knowledge models to provide better structuring of data, information, and knowledge during geoscience investigations.

The emerging field of geoinformatics provides a vehicle for creating the desired 'GeoInfrastructure' and enabling geoscience-knowledge integration. At the present time geoinformatics is concerned with the collection, storage, retrieval, processing, and dissemination of geoscience data, information, and knowledge. As geoinformatics matures it will enhance the active flow of data and information to, and from, process models and decision processes, which will facilitate geoscience knowledge creation. Full implementation of this new GeoInfrastructure allows knowledge to be captured and directed to decision processes.

As geoinformatics broadens, those implementing it are recognising that individual technological advancements are not the only requirement for improved data, information, and knowledge management. To be fully successful, the implemented GeoInfrastructure must enable scientists to maintain their creativity and intellectual freedom while working within basic operational guidelines. Changes in the way in which scientists conduct their investigations may be necessary. Most scientists will likely embrace this paradigm and its new workflows once they realise that it improves the quality of their science and frees up their time and energy to allow for more and better scientific discovery.

27.4.1 Integrative protocols

Because computer technology alone cannot enable geoscience knowledge integration, the GeoInfrastructure must contain integrated, formal, and fully documented protocols. Protocols, which are sometimes called 'business processes', are a collection of activities that integrate various inputs to create a measurable output. The customer measures the value of the output (Nasser et al., *this volume*). In the case of the applied geosciences, the ultimate customer is society.

Protocols can be considered to be rules that direct and facilitate work processes. They vary from simple operational tasks to complex, iterative modelling scenarios. An operational protocol might involve rules that establish how data are saved and formatted, how sets of attributes are predefined, and how data are displayed and visualised. Complex protocols may define how process models feed decision processes, and how decision process results will be used to modify model simulations. These protocols and their embedded rules allow rapid modification and replication of analyses and models, and also facilitate the integration of these analytical results into decision processes.

27.4.2 Enabling geoscientists

The geoscience-knowledge integration protocols cannot focus only on data and information. These protocols must also 'enable' the geoscientists. Individuals and teams of scientists must be provided with the appropriate tools and procedures to ensure integration of scientific context, expertise, intuition, and tacit knowledge. This requirement dictates that geoscience organisations, and geoscientists themselves, change their mode of operation. Effective utilisation of these protocols requires deliberate cultivation of individual professional behaviour so as to promote improved interaction. From an organisational viewpoint, new structures and metrics must be instituted that encourage this interaction and provide appropriate rewards for positively responding to them.

27.4.3 GeoInfrastructure Value

The value of the GeoInfrastructure will be fully realised when it is demonstrated that it can free-up thousands of hours for geoscientists to work more productively by creating new, wide-ranging efficiencies. D'Angelo and Troy (2000), for example, estimated that:

(1) Geoscientists spend 30–70 percent of their time looking for, extracting, reformatting, validating, cleaning up, importing, and documenting data;
(2) Organisations frequently acquire or re-purchase identical data many times, simply because it is faster and cheaper to re-acquire data from vendors than to search internally for the same, already purchased, data that had been subsequently "lost;" and

(3) Up to 40 percent of data acquired by the average operating organisation over the last 10–15 years is missing, corrupted, or otherwise unusable (e.g. stored on obsolete media).

The value of the GeoInfrastructure also lies in the increased time available for actually integrating ideas and tacit knowledge. Once the GeoInfrastructure has been implemented, the emphasis within the integrated "geoscience knowledge organisation" can then be placed on developing a better understanding of natural processes and alternative hypotheses instead of in data manipulation.

27.4.4 Implementation of the GeoInfrastructure

The implementation of the described GeoInfrastructure thus involves a conscious decision to commit an organisation's resources – both people and technology are integral participants. The effectiveness of a geoscience organisation in utilising the "Geoscience Knowledge Integration Paradigm" depends on its willingness and ability to transform its in-place data-management system. The ramifications of this transformation can be understood by reference to the data management maturity model described by D'Angelo and Troy (2000) (see Table 27.2). Using this model they suggest that organisations can assess their current position, from 'base' to 'fully-optimised', in terms of data, information, and knowledge management capabilities and organisational maturity. Because it is common for organisations to overestimate their data management maturity level, accurate assessment requires an honest, unbiased evaluation.

Implementation of the Geoscience Knowledge Integration Paradigm will require organisations and the geoscience community to develop protocols for knowledge integration that enable growth in data-management maturity, so that the full potential of integrated data management can be realised. The GeoInfrastructure will tie the protocols together and facilitate increased data-management maturity.

This evolution is based heavily on operational and organisational realignments. Organizational alignment, as it relates to this GeoInfrastructure, does not change an organisation's core business. Instead, it creates and communicates the necessary changes in vision, work processes, and employee-performance standards required to derive full value from a knowledge-management system. The organisation must fully embrace the new paradigm; it must commit both significant resources and strong management support to realign the organisation to be consistent with "best-practices" and protocols.

When this happens, organisations can realise the maximum return on major technological and employee investments. Without management commitment, support, and attention to the necessary changes in processes and employee performance management systems, only a fraction of the potential value can be realised.

Finally, both line-management and users must "own" the organisational alignment effort. When line managers understand that new work processes are required, they can engage their staffs for solutions that minimise impact on employees (D'Angelo and Troy, 2000).

Table 27.2. Data-management maturity (modified from D'Angelo & Troy, 2000)

Maturity Level (I–V)	Process Performance	Technology Support	Quality and Predictability of Results	Value Determination
V) Fully Optimised: Exploration success rate is close to the development success rate	Processes are almost entirely automated	Data mining expert systems	Almost complete certainty of results is achieved	
IV) Predictable Risk: Ability to routinely reduce uncertainty & data-related risk	Statistically stable processes routinely measured against industry standard performance metrics	Automation and background performance of processes/tasks: automated decision support system	The reliability and predictability of results is significantly improved (i.e. six-sigma vs. three-sigma)	Lower return on investments in data management is accepted in exchange for reduced risks
III) Corporate Competency: Capabilities are institutionalised within the company; enabled by mature technology	Standard, consistent, statistically capable, measurable processes; standardised process performance metrics begin to evolve	Integrated technology designed to enable emerging "best practice" processes; technology suppliers are partners in defining how technology achieves the best results	Good quality results within the specified tolerances most of the time; poorest individual performers improve towards best performers; more leverage achieved on best performers	Measurable; able to recognise costs and benefits; perform cost-benefit analyses and maximise return on investment; more good results faster, with fewer people
II) Managed: Standardised tasks and roles; advanced technology introduction begins	Individuals typically develop & follow a process that "works for them;" processes are not common between individuals or across locations	Non-integrated point solutions designed for specific tasks; individuals have primary responsibility to figure out how to integrate & use technology to achieve results	Variable quality with some predictability; the best individual performers can be put on "business critical" projects to reduce risk and improve results	Anecdotal; based on the capabilities of individual performers & specific memorable events
I) Base: Capable people & heroic efforts	No defined processes; individual performers may follow a different process each time	None or general purpose tools (e.g. Excel, Access); data management is a mostly "personal" function, not a corporate one	Total corporate dependence on individuals; little to no corporate visibility into data management cost or performance; variable quality; low predictability & repeatability of results	Subjective; "gut feel" for performance, costs & value received

27.5 The development of a 'GeoPro' structure

Implementing a GeoInfrastructure within an organisation will provide increased efficiency in the evolution of geoscience knowledge. However, the implementation requires a controlling, or supervisory, protocol that enables management of the requests of geoscientists and society alike. A team of geoscientists within the U.S. Geological Survey charged with conducting a series of hydrogeological characterisation studies has begun to develop such a protocol. Their studies are concerned with the availability and sustainability of groundwater resources within the desert south-western United States. The large geographical area and the multidisciplinary nature of their studies required the collaboration of many individual geoscientists located in diverse locations.

Project managers recognised the need to establish standards and procedures to facilitate collaboration and exchanges so they developed a protocol. They defined their protocol as the "Geoscience Knowledge Integration Protocol" or "GeoPro". GeoPro is based on a collection of integrated protocols that encompass the entire geoscience business process (Figure 27.2).

Several fundamental work processes involved in typical geoscience investigations have been identified and form the basis for the GeoPro structure. GeoPro contains five major components that are shown in Figure 27.2:

1. Technical Core
2. Risk Assessment and Decision Support
3. Workflow Management
4. Information Technology Infrastructure
5. Dissemination

The technical core contains linked sub-processes that enable integration and management of geoscience data, three-dimensional geological models, and numerical process and predictive models. The technical core is fundamentally designed and structured to provide the tools and procedures required by the management, analysis, and evaluation of the uncertainty inherent in geoscience data, information, and knowledge.

As illustrated in Figure 27.2, the Technical Core includes three major functions – data management, framework modelling, and process and predictive modelling. Data management includes data collection and data analysis processes. Data-collection processes involve obtaining new field data as well as acquiring existing data in a variety of formats and structures. Data analysis processes handle how data are selected, perform data quality assessments, facilitates data interpretation, and generation and storage of derived data.

Framework and process modelling cover a wide spectrum of discipline-specific processes, but there are commonalities across the disciplines. Creation of geoscience models of the subsurface involves conceptualisation, preparation of data sets, and definition of model geometry and constraints. These factors, together with determination of initial conditions, property uncertainty, parameter sensitivities, calibration, evaluation, and predictive scenarios are all critical work processes that must be managed during process and predictive modelling. This technical core is supported by decision-analysis tools within the Risk Assessment and Decision Process component, and these are in turn supported by the workflow-management capabilities within the Workflow Management component.

Risk assessment and decision processes must be integrated throughout the investigation. Thus the Risk Assessment and Decision Process component is shown as surrounding and supporting the Technical Core in Figure 27.2. Application of risk assessment and decision processes at multiple stages during investigations helps to ensure that the studies answer the societal questions being posed.

The Workflow Management component guides how the work is performed. It controls the data and information flows within the Technical Core and Risk Assessment and Decision Process components. It also manages and maintains the integrity of the documents (reports, graphs, tables, maps and models) produced during an analysis. It thus has links to the Dissemination component.

The Information Technology Infrastructure component supports processes for managing system security and user authentication, database administration, database connectivity, system configuration, and disaster recovery.

Dissemination of the data, information, and knowledge created by the study is a critical component for demonstrating the value of any geoscientific investigation. The Dissemination component controls the product and information flow. It includes the creation of appropriate metadata descriptions and provides the appropriate versions of reports or data, according to the needs of the requestor.

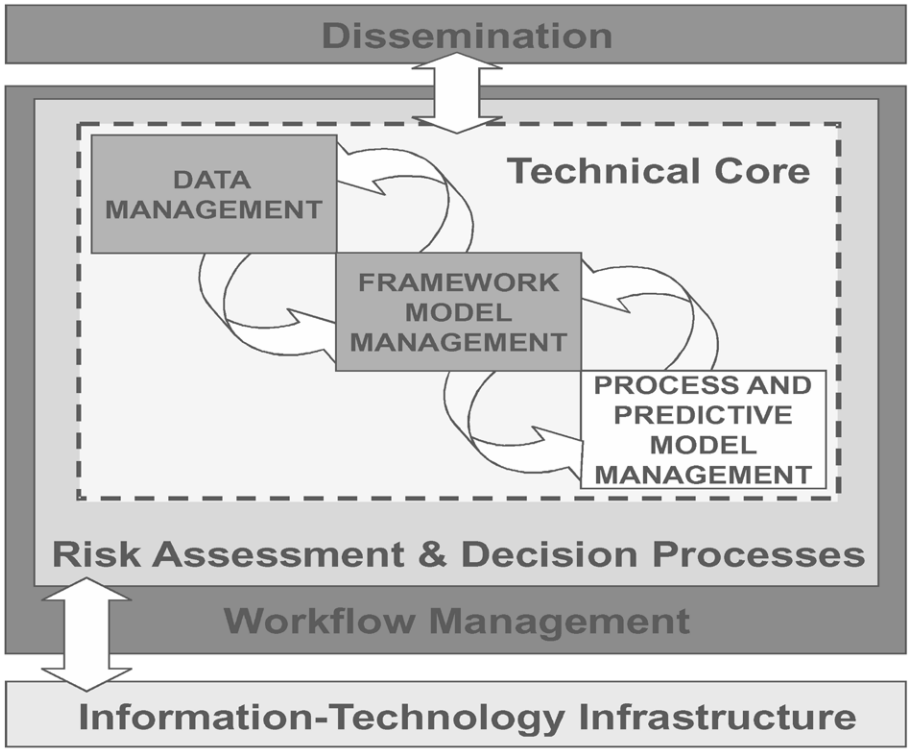

Figure 27.2. Components of the Geoscience Knowledge Integration Protocol (GeoPro)

27.6 The need for standards

The immediacy of societal concerns dictated the need for GeoPro. Unfortunately, this hindered development and implementation of the protocol. The rapid response demanded by society contributes to the short-lived nature of many applied geoscience investigations and are not conducive to good development of standards.

Yet, universally accepted standards enable individuals, organisations, and the entire geoscience community to interact in truly integrated ways that are not currently possible. For example, without standards, the simple task of exchanging data becomes complicated and time consuming, and the data are often inadvertently corrupted. When these difficulties are encountered, further interaction is discouraged and the perceived value of exchanging data and ideas is reduced. Scientists are thus likely return to their isolated work environments and continue to develop their products independently. Only when a client must be provided with a result will the work of numerous independent investigations be 'integrated' into a

unified product from which a solution to a societal concern can be derived. Unfortunately, the independently developed products often may not agree in content, quality, or format and meaningful integration is either difficult and time-consuming, or impossible. Standards will provide the framework within which these independent studies can be based and can enable better integration of results.

Standards will also enable the geoscience knowledge integration protocol to evolve into a stable and secure structure capable of providing accurate and consistent assessments of the quality of geoscience knowledge that are required by society. To be useful in providing competent and prudent solutions, the integrity of the data, information, and knowledge must be preserved. Likewise, maximum impact and acceptance of the protocol demands clearly documented and comprehensive sensitivity and uncertainty analyses be related to and preserved for all data, process, and predictive models. Ultimately, without standards, the protocol cannot be widely implemented and accepted, nor can the paradigm be realised.

27.7 Conclusions

Recent efforts conducted as part hydrogeological characterisation studies concerning ground-water availability and sustainability in the desert south-western United States have encouraged the development of a prototype protocol. This effort demonstrates that it is entirely appropriate for the entire geoscience community (public, private, and academic) to engage in a co-ordinated effort to capture and improve elements of this emerging protocol. By sharing experiences, a stronger, more robust, protocol can be developed and tested in a greater variety of operational environments. Also, no single geoscience organisation has the financial resources or knowledge base necessary to rapidly develop a complete protocol. By sharing experiences and responsibilities, a more effective protocol and a more closely aligned geoscience community will emerge.

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28 Assessment of uncertainties in volume and yield estimations of clastic deposits

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28.1 Introduction

In the Province of Limburg, in the southern part of the Netherlands, land adjacent to the Maas river is regularly flooded during peak discharge. To prevent future flooding, several measures are being considered. Amongst these are the construction of higher quays and embankments, dredging and excavation, the intention being to deepen and widen the river channels. Dredging and excavation will produce an additional benefit, yielding sand and gravel deposits which can be used as construction aggregate. The economic yield from the exploitation of these sand and gravel deposits can be used to offset finance for the flood control works.

To optimally plan excavation and dredging works and obtain a good insight to the financial risk of the project, a thorough insight to the structure of the ground is required. The study focussed on two pilot sites and considered three issues:

1. Global estimation: Methodology to obtain estimates of total volume, tonnage and mean grading of the sand and gravel resources. Estimation should preferably utilise all available data from the site investigations.
2. Financial risk: How to assess uncertainties associated with estimates of total volume, tonnage and mean grading.
3. Local estimation: Optimal planning of dredging and excavation works based on local conditions, e.g. depth to a gravel layer, the lithological composition of the layer, and related uncertainties.

28.2 Site investigation

To establish the ground profile along the river a site investigation was conducted, extending from the most southern (Dutch) part of the river to the city of 's Hertogenbosch in the Province of Noord-Brabant. The site investigation was carried out under the auspices of Rijkswaterstaat, projectbureau Maaswerken. Various types of data were gathered: from shallow boreholes located to establish the thickness and degree of contamination of the superficial clay layer covering the sand and gravel deposits; disturbed and undisturbed sampling from deeper boreholes, to-

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gether with cone penetration tests, to assess the depth, composition and extent of the workable sand and gravel deposits. These boreholes were also used to find the depth of the so called 'substratum', a marine deposit known to lie under the coarse sands and gravels, and likely to consist of fine sands. The top of this substratum forms the bottom of the potentially workable deposits. Dredging works preferably should not extend into this fine-grained material.

Geophysical measurements such as shallow seismics (on water) and electrical resistivity (on land as well as on the Maas) were performed in order to determine the lateral extent and continuity of the workable deposits and their internal structure.

Boreholes samples were used for laboratory particle size analysis and other physical and chemical properties (such as the presence of materials like wood and flint), and to determine the suitability of sediments for use as aggregates for concrete, mortar and other applications.

28.3 Results of the site investigation

28.3.1 General geology of the Maas deposits

The river sediments were deposited during the Late Pleistocene (Weichselian) and belong to the so called Veghel Formation. These consists mainly of coarse grained sediments typical of a braided river system. In general these braided river sediments contain channel deposits as well as bars (both comprising gravels and coarse sands) and overbank deposits (i.e. horizontally layered fine sands, silts and clays). However, the Veghel Formation contains few overbank deposits in the area where the dredging is to be conducted.

The Holocene Maas deposits consist of channel deposits (varying from coarse gravels to fine sands) and fine grained floodplain deposits, laid down in a meandering river system (the Betuwe Formation). During the Holocene, the freely meandering Maas river was able to rework part of the older Pleistocene sediment sequence.

28.3.2 Geology of the southern and northern pilot sites

The river sediments of the Veghel Formation likely to be workable for aggregate in the southern pilot site belong to a more proximal facies than those encountered within the northern site. Borehole logs indicate that sediments in the southern area consist mainly of coarse to moderately coarse gravels and boulders, whereas the sediments in the northern area are moderately coarse to fine gravels, alternating with coarse gravelly sand layers. Considering the lithologies, the potentially workable river sediments of the southern site can be regarded as more homogeneous than the northern area. Figure 28.1 shows two schematic cross sections through both sites.

Within both sites, a fine-grained cover of clay and silt is found on top of the coarse grained sediments (the Betuwe Formation). This layer can reach a thickness of several metres. The bottom of this layer forms the top of the workable deposits.

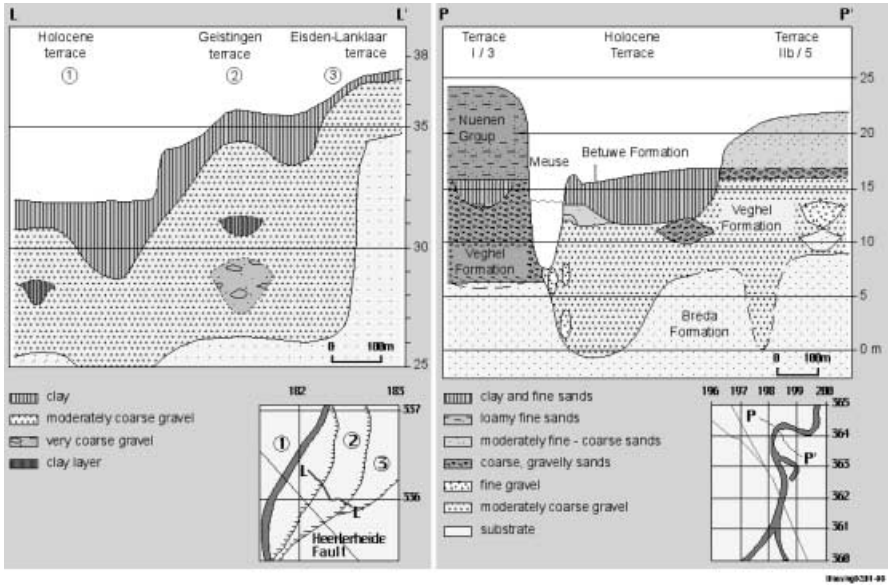

Figure 28.1. Schematic geological cross section through the southern pilot site

Below the coarse river deposits of the Veghel Formation at both sites, the marine fine grained sands of the Breda Formation are distributed; these occasionally contain glauconite grains. Due to its chemical and fine-grained composition this deposit is not suitable as a construction material and so this formation forms the substrate of the workable deposits. On both sites several river terraces can be discerned, as distinct geomorphological edges and as a discontinuity at the bottom of the workable deposits (profile LL' in Figure 28.1).

Through the centre of the southern site runs a NW–SE striking fault: the Breuk van Heerlerheide. However, the offset of this fault does not influence the position of the workable deposit. The northern site is bounded by a NNW–SSE striking fault system: the Peelrandbreuk.

28.3.3 Sources of inaccuracy of data

The information concerning local geology, depth of layers and the lithological composition of each layer was determined from a variety of sources, such as boreholes, cone penetration tests, electrical resistivity and shallow seismics. These various sources of information have varying degrees of accuracy (Table 28.1). For example depths of distinct lithological layers was obtained from several drilling techniques and sampling strategies (disturbed/undisturbed). As a consequence, ac-

curacy of depth determination will differ. Geophysical measurements will yield depths too, but their accuracy will depend strongly on the quality of the interpretation (i.e. the method of interpretation and the ability to correlate with nearby boreholes). The accuracy is related to the type of data, and needs to be taken into account when estimating depths of layers and volume, tonnage or mean grading of resources.

The ranges used in this study to take into account the accuracy of depth determined by the various methods are given in Table 28.1.

Table 28.1. Error ranges used in this study applicable to depth

Data source	Ranges used in this study	Remarks
Borehole logs	+/- 0.25m	Usually considered as hard data
CPT logs	n/d	Usually considered as hard data
Electrical resistivity	+/- 0.5m for shallow layers (top workable deposit) +/- 1.0m for deeper layers (bottom workable deposit)	Always considered as soft data
Seismic reflection	+/- 0.25m	Always considered as soft data Only distinct reflectors are used

28.4 Geostatistics for estimating volume and grading

Geostatistical methods are able to take into account the parameter distribution and spatial variability. Two principal geostatistical tools are applicable: kriging and simulation. For the present application, kriging has some major disadvantages: only a best estimate of depth can be obtained, thus giving a smoothed image of the surface. The individual realisations resulting from stochastic simulation are better suited since they echo the original variability, and thus give a better representation of the roughness of the surface.

A number of simulation techniques are available. Of these, sequential indicator simulation (SIS) is best suited since it takes into account the data values as well as the data configuration when estimating uncertainty. A full explanation of SIS is beyond the scope of this paper, but is published by Govaerts (1997).

The sequential indicator simulation is achieved by transforming the original continuous data values into indicator values at specified cut-off thresholds. These cut-offs are based on the original cumulative distribution function (cdf) of the dataset. For every cut-off threshold a separate variogram is constructed. The indicator approach has as a major advantage that one can model different spatial correlation structures for each separate cut-off value. The pattern of spatial

relation structures for each separate cut-off value. The pattern of spatial continuity may differ, depending on whether the attribute is small, medium or large. The sequential indicator technique can thus model different spatial structures and different continuities for varying cut-offs. Thus 'extreme' structures, such as deep channels, can be modelled as continuous features.

The indicator technique can handle constraint intervals. Soft data can be transformed into indicator values, thereby considering the varying degrees of accuracy for the different sources of information.

The first step in the estimation of total volumes the depth intervals of the workable deposit in all above data types were identified. In both areas the top of the 'substrate' (top of the Breda Formation) and the bottom of the clay cover (Betuwe Formation) were interpreted in boreholes, CPT's and the results of the geo-electrical and seismic measurements. Based on this information 2D-bounding surfaces (top and bottom) of the coarse grained workable unit were modelled. A priori knowledge of the local geological features, such as the presence of the river terraces and the presence of a major fault in the northern area, was taken into account during the modelling and used to group the data into subsets.

As a next step the statistics of these datasets, such as the distribution of depths (represented by the histogram) and the spatial correlation structure of the data (represented by the variogram) was analysed. Special attention was given to outliers, which were omitted or corrected when necessary.

Table 28.2 gives an example of the indicator transformation for the 9 cut-off-values for the top of the workable deposit in the pilot sites, thought from electrical resistivity to lie between 31 and 32 m.

Table 28.2. Indicator transformation for the top of the workable deposits

Proportion	Cut-off	Indicator value	Proportion	Cut-off	Indicator value
P10	30.00	1	P60	32.21	0
P20	30.60	1	P70	32.44	0
P30	31.05	? ⇒ -9999	P80	32.83	0
P40	31.42	? ⇒ -9999	P90	33.26	0
P50	31.71	? ⇒ -9999			

The sequential indicator simulations were performed using the module SISIM of the GSLIB software (Deutsch and Journel, 1992). The simulations resulted in 50 realisations of both the upper and lower bounding surfaces; all 50 outcomes were equally probable. For both surfaces the 50 realisations were then combined to obtain the mean value for the depth of the top and bottom of the workable deposits at each selected grid point. The standard error of estimation of the 50 simulated values provides a measure of the uncertainty at that specific point. Means and standard deviations of the top and bottom surfaces of the workable deposits will give sufficient local information: the estimated depth of the deposits at a particular location and a measure of local uncertainty.

Fifty realisations of the total volume which fall within the planned excavations were calculated by subtracting the bottom from the top for all 50 pairs of realisations. The histogram and cumulative distribution function (cdf) of these 50 volumes give insight in the total volume expected to be recovered and a measure of the uncertainties of these estimates. At this stage however the composition and mean grading of this total volume is still unknown.

Results of the volumes obtained by the sequential indicator technique were compared with those from the analysis based on a random sample of boreholes. In this random sample the thickness of the workable deposit was determined and averaged. The mean thickness of all boreholes was multiplied by the surface of the excavation, which resulted in an estimate of the total volume. The standard error of estimation for thickness in the boreholes was used to calculate the standard error of the mean – which in itself is a measure of the accuracy of the estimate of the total volume. Table 28.3 gives a comparison of the results of both methods.

From these results it appears that when only global estimates of volumes are required the random sampling technique is an efficient tool to obtain these estimates. As opposed to the indicator technique however, the random sampling technique will not give local information on depths of layers and related uncertainties.

The internal lithological structure of the workable deposits strongly determines the mean grading and ultimate economic yield.

The northern pilot site showed a stronger lateral variation of lithology than the southern site. Therefore the categorical sequential indicator simulation was chosen for modelling the internal distribution of gravel, sand and clay within the unit to be worked. Table 28.4 lists the classes which were used to categorise the lithologies.

The stochastic simulations produced 50 equally probable realisations of the spatial distribution of the lithologies (Figure 28.5).

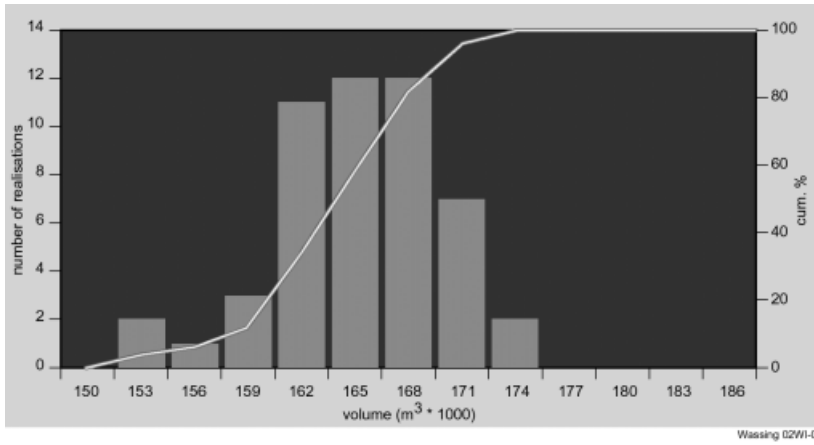

Figure 28.2. Cumulative distribution function for total volume at the northern site

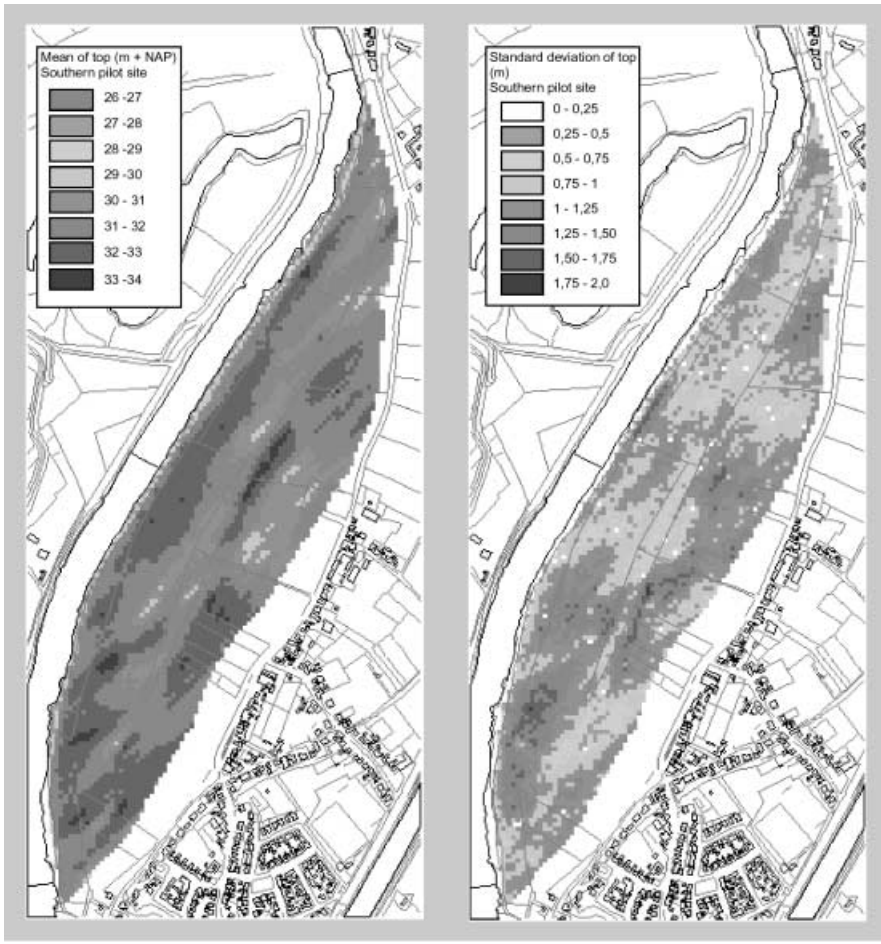

Figure 28.3. Mean elevation of top and associated standard error of estimation for the southern site

All realisations of lithologies were conditioned by the grids of the top and bottom bounding surfaces of the workable deposits, calculated using SIS and the S-grid module provided by g0cad.

For each realisation, the total volume of each individual lithology could be calculated. For every lithology in every realisation, one particular density was drawn from a normal distribution of possible densities. Means and standard deviations for these normal distributions were obtained from literature since no field measurements of densities were available at the time of this study. Then, for every lithology in every realisation, one grain size distribution curve could be drawn from the data set of grain size distribution curves for that particular lithology.

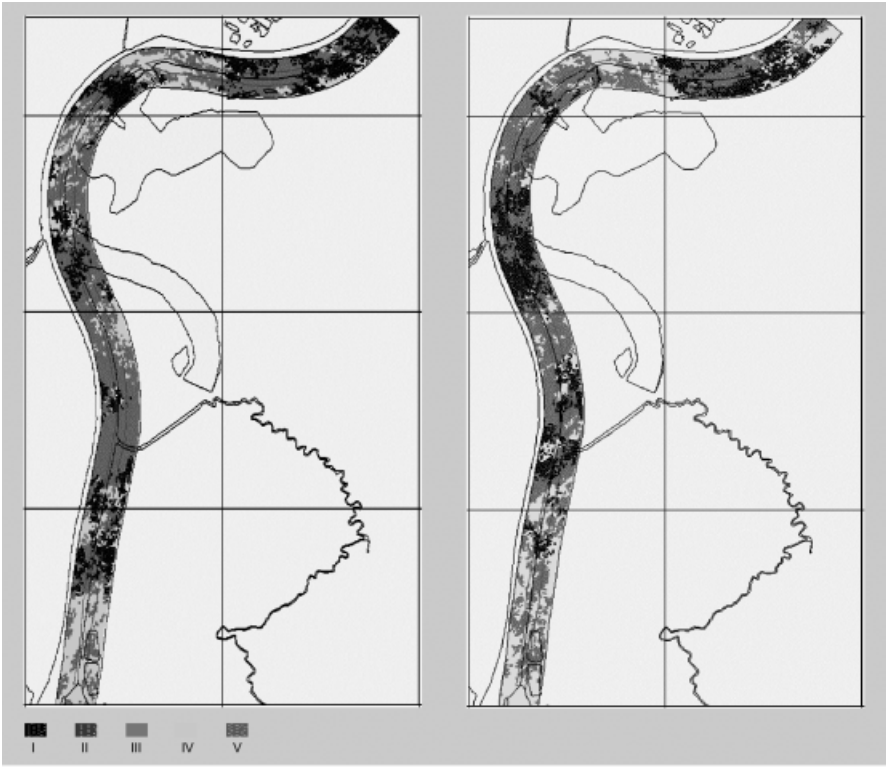

Figure 28.4. Horizontal slice through two 3D realisations of the lithologies within the northern pilot site

The coarse deposit in the southern pilot site consisted mainly of gravel and was far more homogeneous than the northern site. The extra effort required to undertake 3D simulations of the lithology promised little reward and so tonnage and mean grading were obtained directly from the volumes calculated in the first step and the (one) data set of grain size distribution curves for the gravel layer.

Combining the results of all 50 realisations for the southern and northern sites resulted in a graph with total tonnage per individual sieve and mean grading for the complete excavation (Figure 28.5).

Again, the results of the sequential indicator simulation were compared with the results of a simple random sampling technique (Table 28.5). This time the outcome of the random sampling technique differed substantially from the outcome of the indicator simulations. This difference can be partly explained by the fact that the indicator approach required a regularisation of the sample intervals. In the random sampling the original sample sizes were not taken into account.

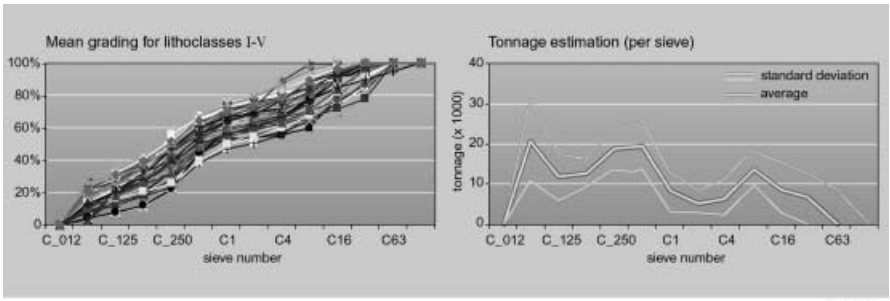

Figure 28.5. Global estimates for mean grading and tonnage with respect to sieve size at the northern site

Table 28.3. Comparing global estimates using indicator simulation and random sampling

	Indicator approach	Random sampling
Estimate of total volume	1.6e6 m^3	1.7e6 m^3
Variation coefficient	2.3%	10.6%

Table 28.4. Lithological categories used in the sequential indicator approach

Class	Category
I	Clay
II	Fine to very fine sands, clayey sands and sandy clays
III	Moderately fine to moderately coarse sands
IV	Coarse to very coarse gravelly sands
V	Gravel

Table 28.5. Comparing global estimates by indicator simulation with random sampling at the southern site

	Indicator approach	Random sampling
Mean of tonnage on 2 mm sieve	3.48e6 tons	3.10e6 tons
Variation coefficient	2.7%	9.0%

28.5 Conclusions

Global estimates of total volume, tonnage and mean grading for potentially workable sand and gravel deposits were obtained by the use of sequential indicator simulation. The individual realisations resulting from the simulation procedure could be used to obtain local information, such as the depth of a certain layer at a specific location together with related uncertainties regarding the estimate. Com-

pared to other geostatistical techniques, sequential indicator simulation offers a straightforward method for handling soft data. It is a powerful modelling tool where spatial continuities of a variety of different geological features like deep channels need to be considered.

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29 Uncertainty with characterisation of soils

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29.1 The Context

The geotechnical characterisation of natural soils can be troublesome. Their behaviour strongly depends on several factors that are difficult to control and their properties usually present a variability that must be taken into account. This is controlled by their geological history, notably the conditions existing during and after the last glacial period and the associated sea level fluctuations.

During the peak of the last glacial period, sea level was about 120 m below its current position. The adjustment of the drainage system to these conditions strongly increased erosive action on the continents, and rivers excavated deep valleys. Since that time, the slow but sustained rise of sea level intensified sedimentation within the previously eroded valleys, typically enriched with organic matter.

29.2 Geotechnical features of natural soils

The associated geotechnical characteristics of such soils may be illustrated in Figure 29.1, showing the effects of consolidation and desiccation. Considerable scatter of σ'_p and OCR values can be expected in the superficial desiccated crust, which is accompanied by scatter in several other (related) physical properties.

Another relevant feature can be deduced from Figure 29.2, illustrating variations in depth of several physical properties at the Bothkennar site (UK) (Hight et al., 1992). These physical properties possess a distinctive variability, characteristic of the deposit and not merely a consequence of insufficient quality of the testing techniques. These authors concluded that the natural variability usually found in soils such as the Bothkennar deposit, is mainly determined by the presence of organic matter.

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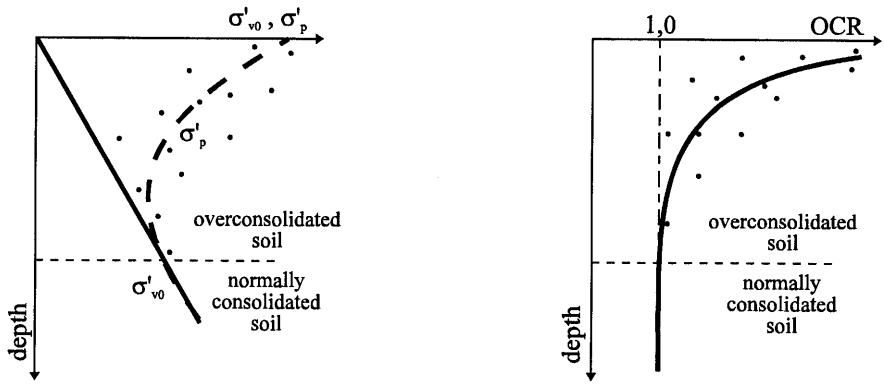


Figure 29.1. σ'_p and OCR profiles in depth resulting from desiccation (Coelho, 2000)

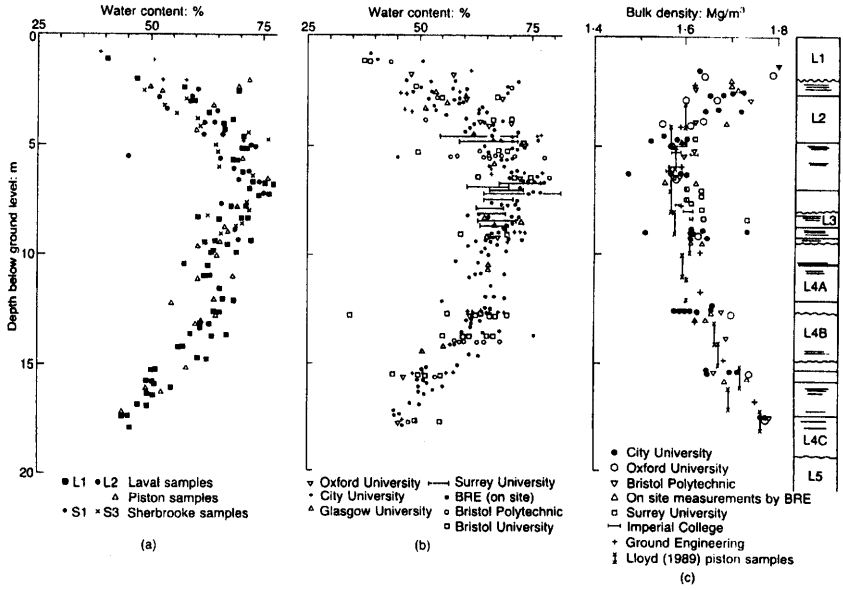


Figure 29.2. Variation in some physical properties with depth at Bothkennar: **(a)** on-site measurements of water content; **(b)** on-site and off-site measurements of water content; **(c)** bulk density (Hight et al., 1992)

Figures 29.3 and 29.4 also express the influence that organic matter can have on soil physical properties, Figure 29.3 illustrating the significant reduction of specific gravity that occurs in the presence of organic matter, as measured by Haan et al. (1994). Figure 29.4 reveals the dependency of soil water content on organic content.

Other influential factors include the existence of shell fragments from marine organisms and cement, notably gypsum and calcite. Sampling is difficult in soft

soils, generally requiring specialist equipment and techniques in order to obtain good quality, intact samples.

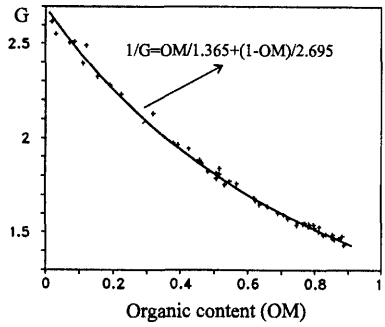


Figure 29.3. Variation of G with organic content (Haan et al., 1994)

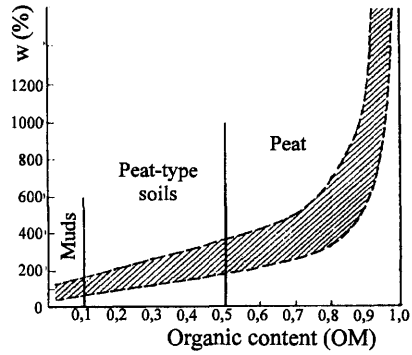


Figure 29.4. Variation of water content (w) with organic content (OM) (Amaryan, 1993)

29.3 Case study: Baixo Mondego

The soil at Baixo Mondego, covering the alluvial plain of the river Mondego, is one of the most significant deposits of soft soil existing in Portugal, both because of its size and the importance of the engineering works being undertaken in the area. As a consequence, its geotechnical characteristics have been investigated in detail.

It is an alluvial deposit composed of the weathered products of granite rock: quartz, mica and feldspar, the latter altering to kaolinite. Silt is the predominant grain size fraction and there is a local presence of organic matter and fragments of shells from marine organisms.

29.3.1 Geotechnical properties

Figure 29.5 illustrates the most important characteristic of the deposit: the soil's variability. There is a large scatter in the physical parameters like w and γ.

Figure 29.6a presents further evidence of the variability, strongly suggesting that this is an intrinsic property of the soil rather than being an effect of some poor quality testing procedure. The variability is typical of almost every physical property represented, notably w, γ, G and e. The degree of saturation (S) is, as expected, always quite close to 100 %. Considering that this is indirectly obtained from the values of other physical properties experimentally measured that also exhibit large variability, it gives additional support to believing the high quality of the results. This figure also portrays the variability of organic matter, which the author considers to be the main feature responsible for the variability found in the

geotechnical properties. The organic constituent of the soil also strongly increases the plasticity, as can be deduced from the plastic and liquid limits not being compatible with the grain size and mineralogical composition.

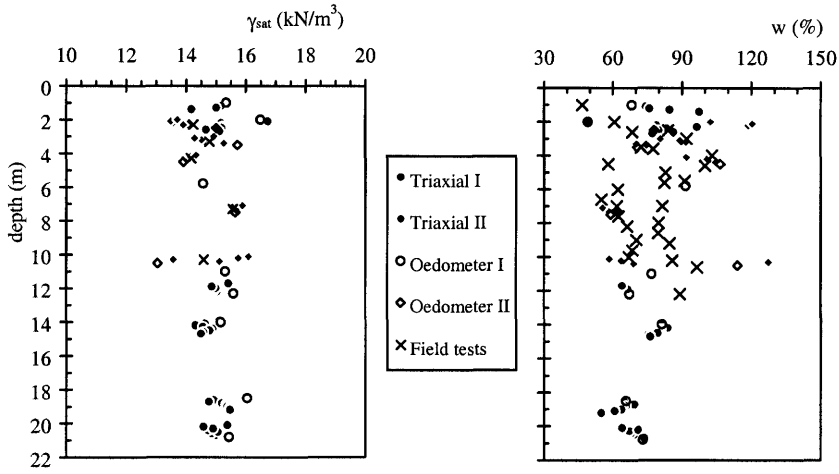
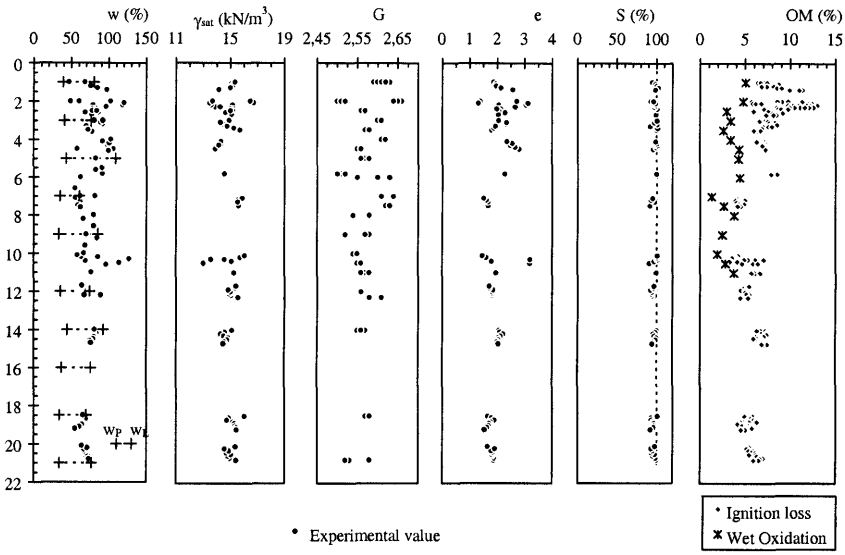


Figure 29.5. Natural variability of some geotechnical properties (Coelho, 2000)

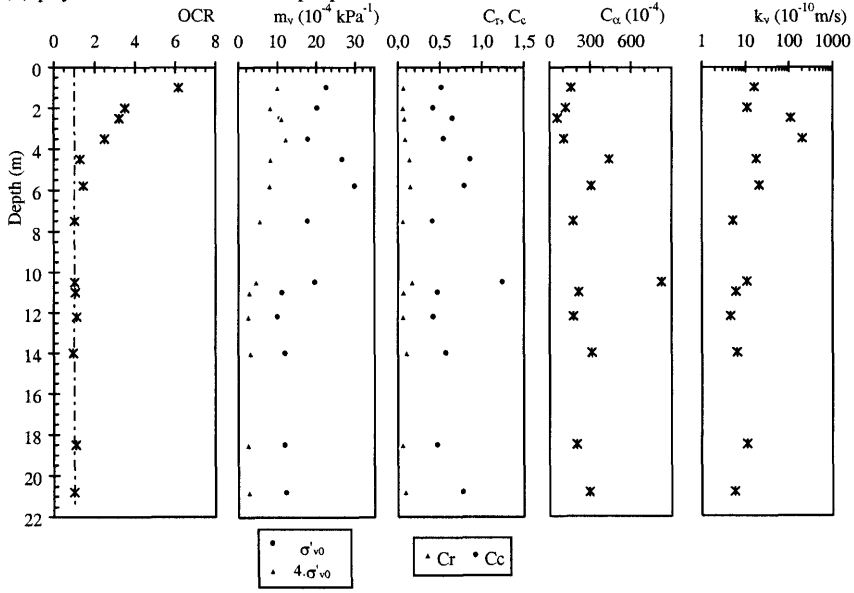
29.3.2 Stress history and consolidation properties

Figure 29.6b presents the geotechnical values measured for several parameters describing the stress history and the consolidation characteristics of the Baixo Mondego soil. As expected from its geological history, the deposit has a desiccated crust at the surface where the soil is clearly over-consolidated. Within this relatively hard crust, OCR values possess a scatter that surely increases the natural variability of the soil's physical condition, although its effects are not expected to exceed those resulting from the presence of organic matter.

In addition, this figure shows that the parameters related to the consolidation properties of the deposit also present a significant variability. Even when considering intrinsic compressibility parameters like C_c or C_r, the range of values measured within the deposit is quite perceptible. C_c, for example, varies between 0.41 and 1.24, values that are not only extremely high in comparison with commonly occurring soils but are also quite distinctive. The high variability can be found in other properties, such as the coefficient of secondary consolidation (C_α), the coefficient of permeability (k), and the undrained shear strength (c_u). The latter strength parameter is the geotechnical characteristic most commonly required to quantify engineering behaviour. The field vane test is a frequently used method to measure its value.



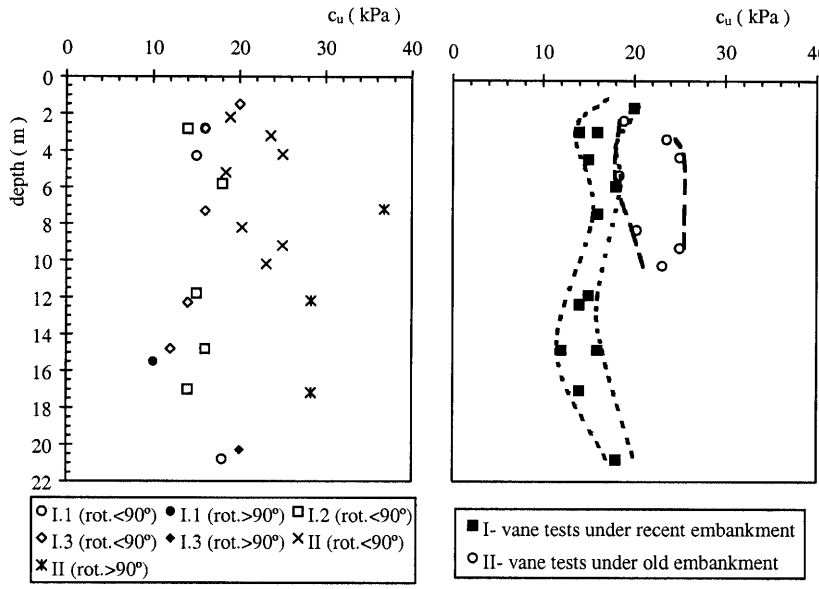
(a) physical and identification properties



(b) stress history and consolidation properties

Figure 29.6. General properties of the Baixo Mondego soil (Coelho, 2000)

Figure 29.7a portrays the values of the undrained shear strength obtained during the ground investigation, again showing very high scatter. However, inspection of the results shows that the rotation of the vane at failure exceeded 90° on several tests. This is unacceptable and is probably caused by fragments of shells jamming the vane. Selecting only those results which failed below 90°, Figure 29.6b yields a more stable pattern of c_u.



(a) all values measured in the field **(b)** analysis of selected values

Figure 29.7. Undrained shear strength as measured by the vane test (Coelho, 2000)

Although the increase in undrained shear strength with time following embankment construction clearly results from a time-dependent increase in the soil effective stress, some uncertainty still remains regarding the values measured. Perhaps this is due to the unavoidable effects of disturbance, especially at shallower depth where the soil sensitivity tends to increase with lower OCR.

29.4 Practical implications

The results suggest that, in practice, a greater number of tests is required to achieve equal confidence concerning the experimental results obtained in soft soils than with stiffer materials, exacerbated by the (usual) presence of organic matter. The consequence is a high scatter on geotechnical properties. Care has to be taken

to include an assessment of the effects of disturbance that could otherwise lead to quite misleading conclusions.

When characterising a soft soil, the presence of organic matter can significantly alter the behaviour that would be anticipated for a comparable inorganic soil, even if the organic matter is only a minor constituent.

Acknowledgments

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30 Analysing uncertainty when modelling geological structures

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30.1 Introduction

There is uncertainty when modelling geological structures located in Precambrian crystalline bedrock. In Finland and Sweden this is typically granite or gneiss in composition and subjected to polyphase metamorphism. The uncertainty in lithology and tectonic structure has been considered for three sites ('A', 'B' and 'C') as part of a comprehensive study undertaken for the Swedish Nuclear Fuel Waste Management Co. (SKB) (Saksa and Nummela, 1998). This has been supplemented by information from the Olkiluoto site modelling, in Finland, and discussed in the context of fracturing and its intensity (Ch. 4.4 in Vaittinen et al., 2001).

30.2 Sources of uncertainty

Uncertainty is an inherent characteristic of all ground investigations. The major sources originate from measurements (errors in data, sampling limitations, scale variation) and concept (structural geometry and properties, ambiguous geometric or parametric solutions). These may be considered as follows:

- **Geological concept** (evolution, deformation phase, age, relationships, descriptive forms, analogues, style related to cartographic presentation)
- **Measurement** (sampling limitations, spatial distribution, coverage)
- **Structural geometry** (zonation, continuity, planarity, relationship to lithology, anisotropy, system complexity)
- **Structural properties** (generic data, discrete data, variability)
- **Error** (in observations, in interpretation, in correlation, with integration)
- **Inconsistency** (definitions missing, varying cut-off values, subjective lineaments, representative vs. interesting)

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- **Scale** (transfer between scales, generalisation)
- **Unknown lithology or structure** (resulting from unsampled volumes, site conditions, available investigation methods, noise).

30.3 Methodology

The principal approach has utilised the classical expert review of site investigation data and modelling results. To supplement this, the following treatment of uncertainties was carried out:

- Compilation of survey tables and maps (with the help of GIS and CAD software)
- Comparison with tables and maps
- Comparison of concepts and site definitions
- Assessment of borehole data: deterministically and statistically
- Fieldwork to evaluate the site and overburden conditions
- Data quality checks of original data, methods and interpretations
- Calculation of thematic uncertainty indices for all sites.

A difficulty recognised at the outset lies in detail, in source data and interpretation. An example which depicts both varying levels of detail and scale variation is presented in Figure 30.1. On the left, the map at a regional scale (~10 km) portrays summarised results and no uncertainty. In the middle, borehole data from fracture zone intersections displayed at a site scale (1 km) show much more detail. It is evident that a number of possible interconnections and interpretations is possible. On the right, fracture orientation data at a detailed scale (10 m) permits several alternative interpretations to be made for one particular borehole section; the degree of associated uncertainty is thus considerable.

Another source of uncertainty relates to the concept criteria applied. A specific example is the fracture zone criteria used in site scale modelling. Fracture frequency is a parameter commonly used to delineate fracture zones. At sites 'A' and 'C' a cut-off value of 10 fractures/m was utilised, at site 'B' the value was 6 fractures/m. This means that in a similar fracture state, the site 'B' model will include more fracture zones than the other sites. If site 'B' is used as a reference, sites 'A' and 'C' will have higher uncertainty (more missing structures) regarding the determination of the fracture zones. Fracture frequency may be related also to the size of structures (length, continuity) and, if the criteria used varies, this may show up in the geometry of the structure.

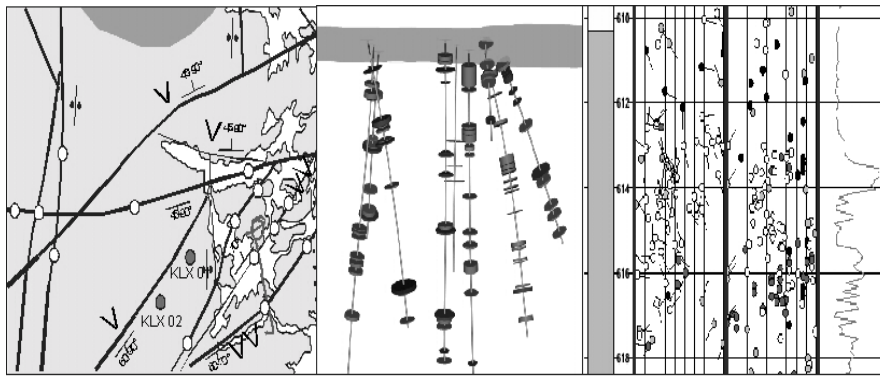

Figure 30.1. Visualisation at three different scales demonstrating how uncertainty can become hidden in the detail

30.4 Case Study

30.4.1 Main site characteristics

At site 'A' the development of a regional model has been thoroughly performed. At the site scale, a major source of uncertainty concerns the absence of a clear definition of the target area. Structures encountered in the boreholes are well explained and an interdisciplinary approach to interpretation has taken place. A large part of site 'A' was covered by sea (40 %), inhibiting geological and the geophysical studies of the bedrock except for airborne magnetic and seismic refraction. It has certainly had a masking influence.

Model development at site 'B' used half the available methods at a regional scale. Mostly this means that some general methods have not been used, but exceptionally it may mean that acquired data has not been used. The site area was thus unclear and a complicated survey pattern evolved (Figure 30.2). The legend illustrates the situation normally met at a site: boreholes were placed to investigate anomalous situations or where average ground was anticipated.

Geological investigations produce points, lines or areas. Such surveys are often conducted as part of the characterisation programme but some surveys have somewhat specific goals and spatial targets. Figure 30.2 contains uncertainties related to coverage and density of investigation, indicated in a qualitative manner. The model for site 'B' accounts for half the fractured sections encountered in boreholes; consequently large amounts of data remain without being interpreted.

Regional models for sites 'B' and 'C' contain relatively large uncertainties due to the investigation methodology and limited experience available at the time of the investigation (1970s–80s). At a site scale, six additional structures were proposed at both sites. Uncertainty was detected in the form of fractured sections along the boreholes that had not been interpreted. At site 'C', the regional lithology was a possible source of additional structures that had not been analysed. The

lithological properties were also not known (because they had not been investigated), for instance major dolerite dykes.

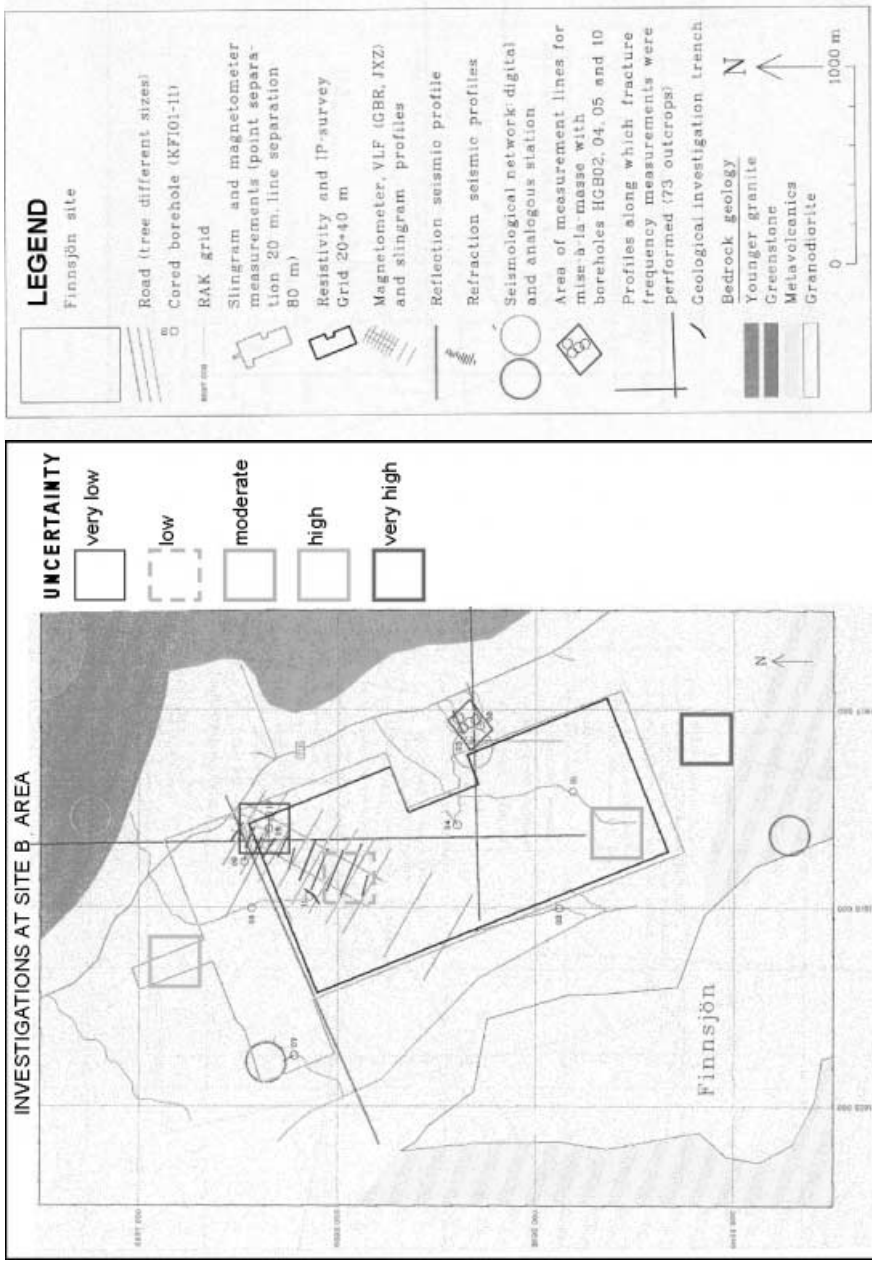

Figure 30.2. Surface map of ground investigation at site B. Uncertainty distributions are illustrated for example areas

During this study, no major differences in concept between the sites were noted. One source of uncertainty in the site modelling was the apparent absence of structures at a scale of 10–300 m. In practise these correspond to features such as long individual fractures, fracture swarms and minor fracture zones (typically a few metres thick). Such fractures were partly incorporated at site 'A' by 'hydraulic structures', but not recorded at sites 'B' or 'C'. Fractures at a smaller scale (size <10 m) were described as 'fracture system'. However, fieldwork showed that such structures could easily be recognised and were indeed present. An example is shown in Figure 30.4 from site 'C', revealing one long fracture running tens of metres along an obvious exposure.

30.4.2 Applying a statistical model

Analysis of structural models utilises the spatial distribution and frequency (density) of features. Frequency is a measure of the number of structures per unit volume. A deterministic analysis is not possible due to the lack of data coverage so use is made of statistical estimates utilising borehole data. A method has been developed which simulates the fracture zone network. Five geometrically different structural systems were devised for simulation and the results calibrated to match the borehole observations. The structures are described by plane surfaces with no thickness (Figure 30.3) (Saksa and Nummela, 1998).

Statistical analysis revealed high occurrences of structures at all three sites, typically 20–30 structures/km^3 with each structure assumed to be planar and having a normalised surface area of 1 km^2 within each 1km^3 of volume. Comparison with structures in deterministic models results in one measure of the uncertainty, parameter SKU (section 4.3). In addition, configuration of the borehole network was inspected to find whether preferences or factors causing bias were present. Indeed borehole network and orientations did have some influence on uncertainty.

30.4.3 Uncertainty ratings

Comparisons between the sites require a quantitative approach, measured by absolute indices or relative ratings. Such measures can be derived by normalising the values between 0.0 (very low uncertainty) and 1.0 (very high uncertainty).

Five different uncertainty indices were developed and calculated for the regional and site scales on the basis of borehole data, representativeness and structural knowledge (Saksa and Nummela, 1998):

- Regional scale uncertainty, RSU
- Site scale uncertainty, SSU
- Borehole data uncertainty, BDU
- Borehole representativeness uncertainty, BRU
- Structural knowledge uncertainty, SKU

Values of RSU and SSU were calculated from a number of the investigation methods used. They effectively describe how extensively the sites have been studied. BDU is derived from the observations in the boreholes and how well they could have been described by a corresponding deterministic model. BRU utilised parameters from borehole covered volumes, nominal site volumes and borehole lengths per borehole covered volume. SKU utilised statistical and deterministic measures of the structures.

The calculation results are presented in Figure 30.5. Site 'A' has SKU and BRU values which are higher, and RSU and BDU values lower, than the other sites. Sites 'B' and 'C' have the highest calculated RSU and BDU values. Considerable uncertainty exists for all site volumes in terms of structural knowledge SKU. Uncertainty regarding borehole representativeness is rather high at site 'A', which stems from the fact that a small volume has been studied which may in fact form an independent tectonic unit. Two sites have high uncertainty indices as far as regional scale models are concerned.

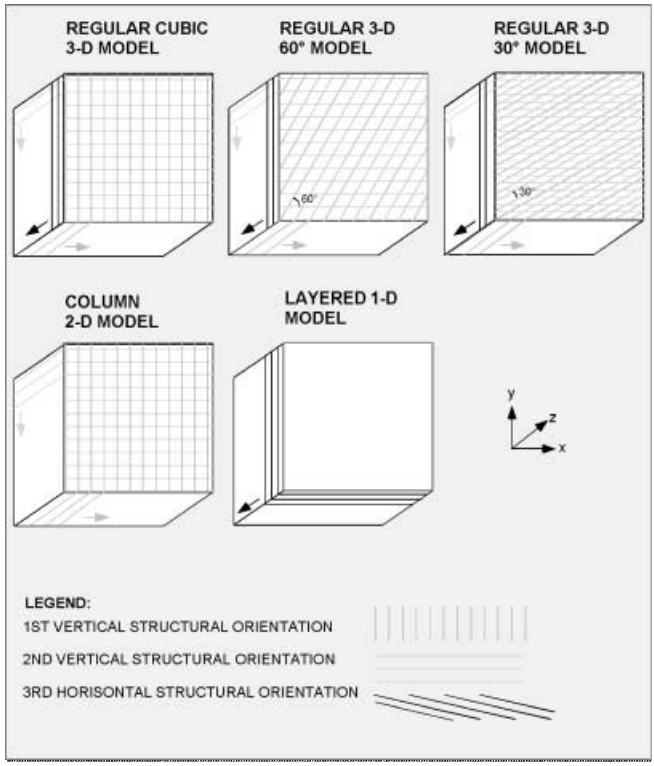

Figure 30.3. Simulation models for the various structural systems

Figure 30.4. Single long bedrock fracture revealed in exposure; scale of tens of metres

30.4.4 Uncertainty aspects concerning the Olkiluoto site model

A further uncertainty analysis was done as part of the geological modelling for the Olkiluoto nuclear waste investigation site in Finland (Vaittinen et al., 2001). Modelling utilised the new ROCK-CAD™ NT software which links to AutoCAD 2000. The purpose of the uncertainty analysis was to steer future investigations, and to depict realistic geological conditions when the detailed site investigations have yet to be finalised.

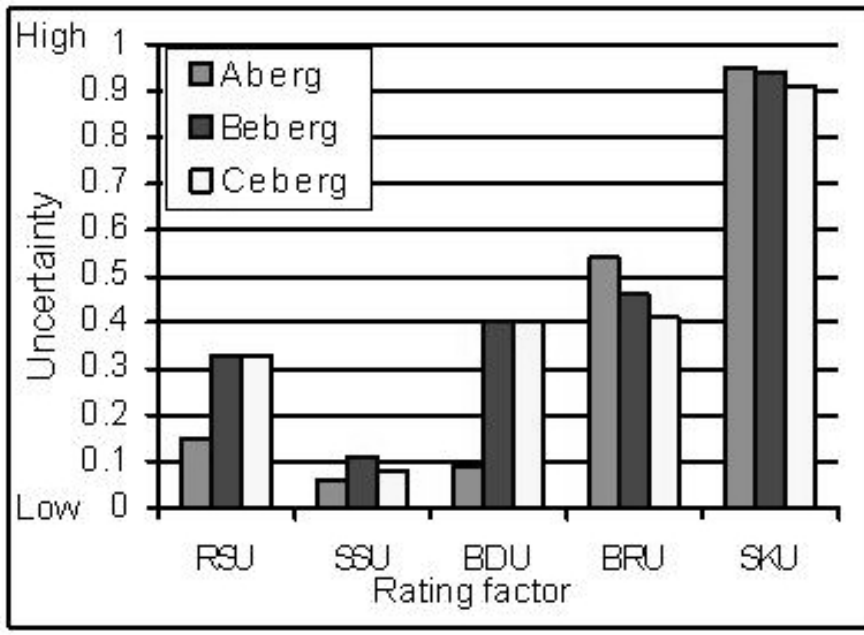

Figure 30.5. Uncertainty indices for themes evaluated at sites 'A', 'B' and 'C'

The results showed for both observed and estimated components that improved repository siting and lay-out planning could be achieved. An example of a surface map illustrating both observed and simulated structures is given in Figure 30.6.

Such statistical models, together with the Fracman code for fracture modelling (Dershowitz et al., 1994), were used to simulate unknown structures. Based on the simulations and analysis of the borehole data it was concluded that about half of the existing structures had not yet been incorporated in the deterministic model. Most of the unknown structures were local ones, the more extensive crushed zones and major fracture zones were already reasonably well known.

It was also recognised that uncertainty exists in a way which can lead to alternative interpretations and model realisations. This is a normal situation for any geological investigation. To be able to express this type of uncertainty, a measure for interpretation reliability or certainty has been developed (Vaittinen et al., 2001). Each interpretation with alternatives has a rating, and compared with a base case model which is built from the most certain, direct observations and indirect interpretations available.

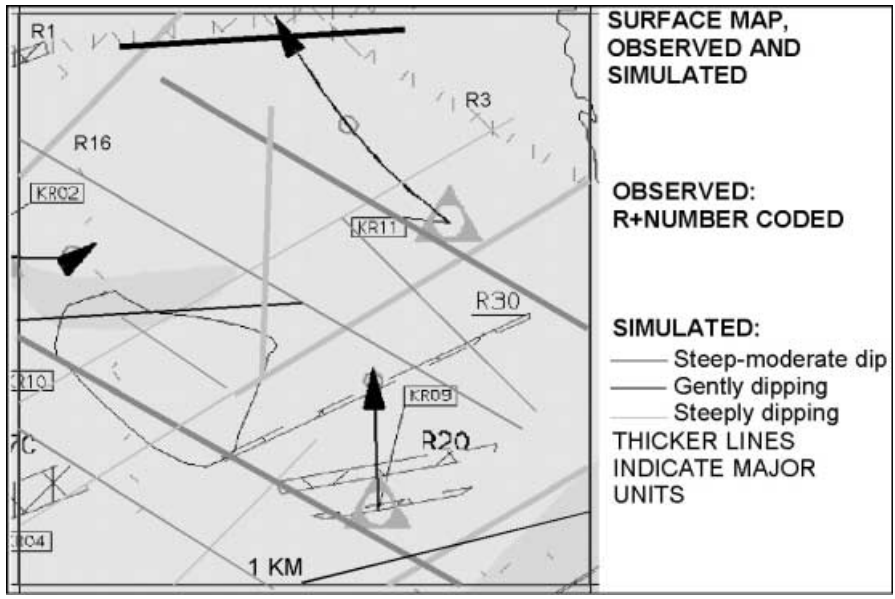

Figure 30.6. Extract from the Olkiluoto surface map, containing observed and simulated (unknown, uncertain) structures

30.5 Conclusions

Uncertainty analysis for structural models becomes easier if investigations and data analysis are documented and executed as systematically as possible during site characterisation. Uncertainty analysis should be kept in mind during the data collection phase. Interpretation rules and techniques need to be documented. The use of data needs to be traceable and any integration work described. In other words, there is a need for metadata and quality assurance of the geological modelling.

The statistical analysis offers one method which can be developed further. New tools are needed for quantitative analysis of structural models, perhaps forming a bespoke set of tools similar to those currently used for geological modelling itself.

Acknowledgements

The studies have been funded by Svensk Kärnbränslehantering AB (SKB), Sweden and Posiva Oy, Finland. The authors would like to thank Anders Ström and Lars O Ericsson from SKB. Their interest in the topic, continual support and patience have made this study possible. Anders Ström kindly gave permission for publishing the material from SKB. The authors express their gratitude to Liisa Wikström and Aimo Hautojärvi at Posiva Oy who have led the site characterisation and modelling efforts for the Olkiluoto site.

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31 Uncertainty characterisation: reliability methods for slope stability

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31.1 Introduction

Geotechnical engineering has to deal with significant uncertainty of the variables determining behaviour. Despite these uncertainties, geotechnical engineers have traditionally used a deterministic approach, in which uncertainty is managed by recognising that risk and uncertainty are inevitable and inherent to any project (Christian et al., 1994), and by applying the observational method (Peck, 1969), or using the concept of calculated risk (Casagrande, 1965).

Even though most engineers are aware of the difficulties surrounding the term Factor of Safety (Whitman, 1984), the concept itself is simple, and it is in fact widely used in common practice. The Factor of Safety provides a deterministic framework to manage uncertainty, within which safety is 'assured' by the election of an 'adequate' value for the Factor of Safety. This is based on engineering judgement and experience, taking into account other factors such as the scatter of the data and the proposed construction procedure (Kalamaras, 1996).

Subjectivity is inevitably inherent to the deterministic approach. Different sources of uncertainty cannot be readily compared, analysed or quantified.

The probabilistic approach appears to offer a promising alternative method for providing a framework in which uncertainty is treated in a quantitative and systematic manner. Despite the capacity of the probabilistic approach to deal with uncertainty, its incorporation within geotechnical practice has been less than in other branches of engineering (Christian *et al.*, 1994), for a number of reasons (Kalamaras, 1996; Juang *et al.*, 1998; Whitman, 1984).

However, the introduction of new standards and recommendations that propose reliability-based designs is leading to increased interest in the probabilistic approach. There are new challenges, such as the need to optimise designs based on minimal exploratory data and the need to work on non-traditional problems, contributing to the extension of probabilistic geotechnical design practice (Kalamaras, 1996).

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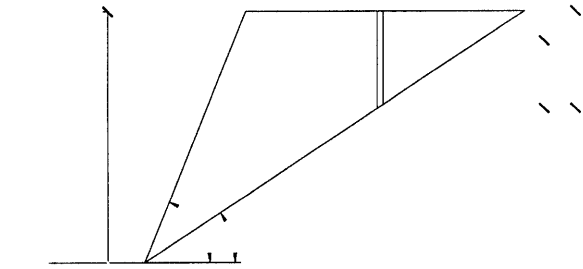
31.2 Model formulation

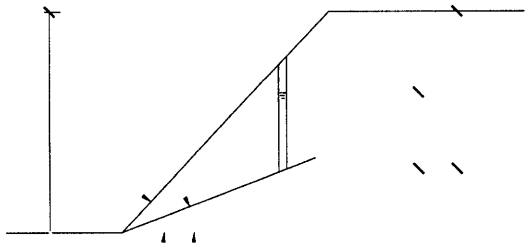
The first step of a reliability analysis is to establish a clear delimitation between success and failure (Whitman, 1984). These terms might mean something other than the actual stability or collapse of an engineering structure, for example the occurrence of satisfactory or unsatisfactory performance.

As an example, the reliability of a rock slope has been taken in which failure might occur along a single plane surface. To model the behaviour of such a slope, the approach developed by Hoek and Bray (1981) will be used in this section.

The kinematic conditions for admissibility are first considered with respect to planar sliding: (1) the plane (α_p) must strike parallel or nearly parallel to the slope face (α_f), thus $\alpha_f = \alpha_p \pm 20°$, (2) the failure plane must 'daylight' in the slope face ($\psi_f > \psi_p$), (3) the dip of the failure plane must be greater than the angle of friction of this plane ($\psi_p > \phi$), and (4) release surfaces must be present in the rock mass to define a lateral boundary or, alternatively, failure can occur on a plane passing through a convex 'nose' of the slope.



1. Failure Mode 1



(b) Failure Mode 2

Figure 31.1. Possible failure modes of the planar slope under consideration

Once these conditions for plane failure kinematic admissibility are satisfied, the rock slope will be considered to fail once the Factor of Safety, defined as the ratio between the resisting and driving forces when projected in the direction parallel to the failure plane, is less than unity ($FoS < 1$).

Two different failure modes may be differentiated, depending on the location of a tension crack within the slope. The first failure mode represents a slope having a tension crack in its upper surface, whereas the second one represents a slope with a tension crack in its face, as shown in Figure 31.1. The transition between both failure modes will occur when the tension crack is located at the slope crest, i.e. when:

$$\frac{z}{H} = (1 - \cot\psi_f \cdot \tan\psi_p) \tag{1}$$

The general expression of the Factor of Safety for both failure modes will be:

$$F.S. = \frac{c \cdot A + (W \cdot \cos\psi_p - U - V \cdot \sin\psi_p)\tan\phi}{W \cdot \sin\psi_p + V \cdot \cos\psi_p} \tag{2}$$

where c is the cohesion of the plane-block interface, ϕ is the friction angle, A is the area of contact between block and plane, U and V are water pressure resultant forces, and W is the weight of the rock block. From Figure 31.1 it can be computed that A, V and U have the following values (Hoek and Bray, 1981):

$$A = (H - z)\csc\psi_p \tag{3}$$

$$U = 1/2\gamma_w z_w (H - z)\csc\psi_p \tag{4}$$

$$V = 1/2\gamma_w z_w{}^2 \tag{5}$$

The expression to obtain the weight of the block whose stability is of interest is dependant on the failure mode. Equation (6) gives the weight of a block with a tension crack in the upper slope surface (failure mode 1), whereas equation (7) gives the weight of a block for the case where the tension crack is located in the slope face (failure mode 2):

$$W = 1/2\gamma_{rock}\ H^2[(1-(z/H)^2)\cot\psi_p - \cot\psi_f] \tag{6}$$

$$W = 1/2\gamma_{rock}\ H^2[(1-z/H)^2\cot\psi_p(\cot\psi_p\tan\psi_f - 1)] \tag{7}$$

Once the equations that govern the performance of the slope have been defined, criteria can be established to assess the likelihood of occurrence of failure in the slope. Thus a set of limit state functions are defined by an equation of the form $g(x_1, \ldots, x_n) = 0$, in such a way that $g(\mathbf{x}) > 0$ for all values of the input variables $\mathbf{x}$ in the interior of the safe zone, and $g(\mathbf{x}) \bullet 0$ for all $\mathbf{x}$ inside the failure zone. The limit state functions considered here are as follows:

$$g_1 \equiv z - H(1 - \cot\psi_f \tan\psi_p) \leq 0 \tag{8}$$

$$g_2 \equiv F.S.(Failure\ Mode\ 1) - 1 \leq 0 \tag{9}$$

$$g_3 \equiv F.S.(Failure\ Mode\ 2) - 1 \leq 0 \tag{10}$$

$$g_4 \equiv \psi_p - \psi_f \leq 0 \tag{11}$$

$$g_5 \equiv -\psi_p \leq 0 \tag{12}$$

where $g_1 \bullet 0$ indicates occurrence of failure mode 1, $g_2 \bullet 0$ indicates failure supposing failure mode 1 happens, $g_3 \bullet 0$ indicates failure supposing failure mode 2 happens; $g_4 \bullet 0$ and $g_5 \bullet 0$ verify conditions for kinematic admissibility.

These limit state functions may be combined to determine the performance of the slope and the occurrence of either of the failure modes. Each is represented by a parallel system of limit state functions, so that for failure to occur in one of the failure modes all the limit state functions defining that specific failure mode must verify the condition $g_i(x) \bullet 0$. The limit sate function $g_1(x)$ has a different sign in the definitions of both of the failure modes (note that for failure mode 2 to happen, $-g_1(x) \bullet 0$ must be verified). This definition makes the failure modes disjointed, i.e. $E_1 \bullet E_2 = \emptyset$, where E_i represents the occurrence of failure mode i.

Representing the slope as a general system reliability problem composed of disjointed parallel subsystems allows calculation of the total probability of failure slope by summing the probabilities of failure of each one of the failure modes.

31.3 Statistical characterisation of input variables

A probabilistic description of the input variables is necessary when significant uncertainty is evident from the geotechnical site characterisation. Reliability methods would then appear to be the logical choice to complement a probabilistic subsurface characterisation procedure. In the case study under consideration, some of the input variables have been modelled as deterministic quantities whereas others have been modelled as random variables, depending on the range of variation that would be expected *in situ*, and on the consequences of that variability for the expected performance of the slope. This might be assessed by means of a series of sensitivity analyses.

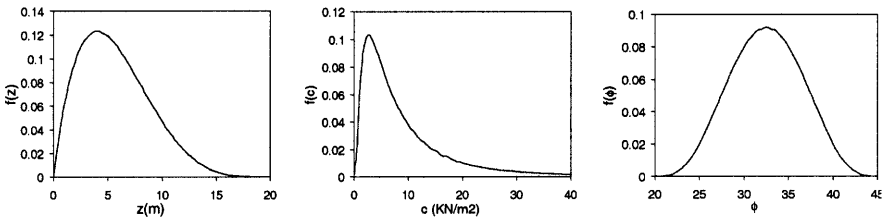
The following deterministic parameters have been identified: the height of the slope 'H' and the slope face angle '$\psi_f = 60$', which can both be closely controlled during construction, the failure plane angle '$\psi_p = 30$' which is supposedly known quite accurately, and the unit weight of rock, '$\gamma_{rock} = 28$ kN/m^3'. The drainage system has been assumed to function properly, so that the slope may be considered to remain in a dry condition.

There is a complementary set of input parameters for which estimation uncertainty has been considered to be significant, such that they would best be modelled as random variables. These parameters are the depth (uniquely related to position)

of the tension crack 'z', the cohesion 'c' and the angle of friction 'ϕ'. Table 31.1 shows the types of distributions used to model each of the random variables considered, as well as the values of the parameters used to describe the corresponding distributions. The selection has been done based on judgement and on published strength values obtained from back analysis of rock slope failures (Hoek, 2000). Figure 31.2 shows the probability density functions (PDF) considered for each of the random variables.

Table 31.1. Statistical description of random variables

variable	p1	p2	p3	p4	μ	σ	Distribution
z	q = 2.0	r = 5	a = 0	b = H	5.7	3.2	*Beta*
c	μ = 10.0	σ = 12			10.0	12.0	*Lognormal*
ϕ	μ = 32.5	σ = 4	a = 20	b = 45	32.5	4.0	*Beta*



(a) Tension Crack depth (z) (b) Cohesion (c) (c) Friction angle (ϕ)

Figure 31.2. Probability density functions of the random variables

31.4 Reliability of a single component

31.4.1 Analytical method

In order to assess the reliability of the system, an estimate of the reliability of each of the single components first needs to be determined. Each component is defined using one of the limit state functions presented above, defined in a way such that it is considered to fail when $g_i(x) \bullet 0$ (or alternatively, $-g_i(x) > 0$ when $-g_1(x)$ is used as the limit state function). The probability of failure may then be computed as:

$$P_f = P(g(x) \leq 0) = \int_{g(x) \leq 0} f(x)dx \tag{13}$$

where $f(x)$ is the joint PDF of the input variables that enter that limit state function.

An alternative measure of safety is given by the generalised reliability index (Ditlevsen, 1979), which is related to the probability of failure by the following expression:

$$\beta_g = \Phi^{-1}(1 - P_f) \tag{14}$$

where $\Phi(\cdot)$ represents the cumulative density function (CDF) of the standard normal distribution.

The direct computation of integrals such as presented in (13) is often a very complex, computationally intensive task when standard methods of numerical integration are used. For that reason, a number of methods have been developed to compute probability integrals in the form of (13). Between them, the first and second-order reliability methods (FORM and SORM) have found the widest acceptance, together with simulation methods such as the Monte Carlo simulation method and the first order directional simulation method.

FORM and SORM are analytical methods used when the basic variables have strictly increasing continuous joint CDF's. They consist of a number of steps (Bjerager, 1990): (1) transformation of the basic variables, into standard and uncorrelated normal variables (in the so-called standard normal space), (2) determination of the most likely failure point in the standard normal space $\mathbf{u}^*$, also called the design point, (3) approximation of the limit state surface in the standard normal space at the design point, and (4) computation of the probability of failure in accordance with the approximation surface selected in step (3).

Figure 31.3 shows the transformation from the original space to the standard normal space used for the random variable cohesion, together with the PDF's of the random variable in both spaces (these values have been scaled for visualisation purposes). As the variables considered in this work are non-normal, uncorrelated random variables, the transformations used are of the type: $F_U(u(x)) = F_X(x)$, where $F(\cdot)$ represents the CDF of the random variables in the original and transformed space. For other situations Der Kiureghian and Liu (1986) and Hohenbichler and Rackwitz (1981) review the most common transformations. The transformations for z and ϕ were performed in an equivalent manner.

The determination of the design point is obtained as a solution to the following optimisation problem:

$$u^* = \min\{\|u\| \quad |G(u) = 0\} \tag{15}$$

The design point is also known as the most likely failure point, since it has the highest probability density among all points in the failure domain in the standard normal space. Several algorithms have been proposed for the solution of this problem. Having compared a number of them, Liu and Der Kiureghian (1991) concluded that the HL-RF method required the least amount of storage and computation, even though they reported situations in which the method may fail. Zhang and Der Kiureghian (1995) proposed the improved HL-RF algorithm which assures the convergence to a solution of (15).

The approximation of the limit state function in the standard normal space will be a first order approximation (hyperplane) in the FORM method, whereas it will be a second order approximation (parabolic surface) in the SORM method. Figure 31.4 shows an example of the approximating surfaces in the standard normal space for a two dimensional case. It may be noticed that the second order approximation provided by SORM better incorporates the influence of the curvature of the limit state surface in the probability of failure.

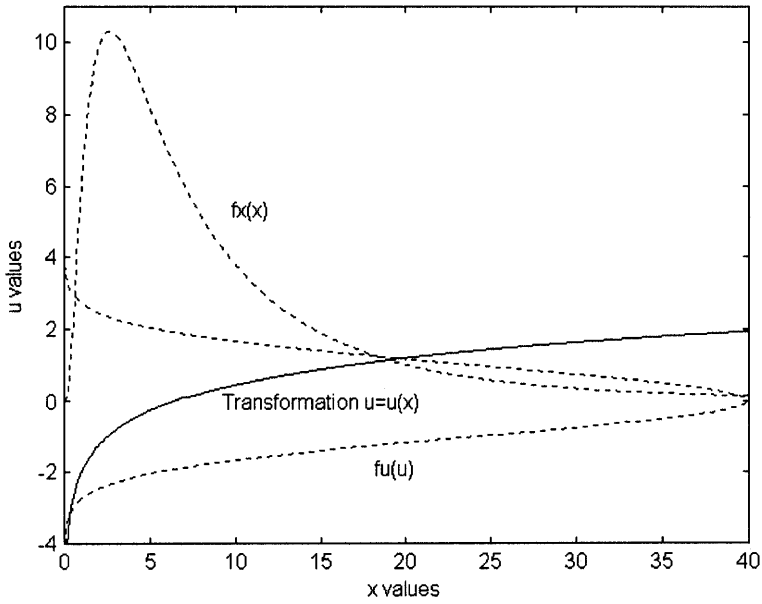


Figure 31.3. Transformation of the cohesion from the original space to the standard normal space

The probability of failure of each approximation will then be given by the following expressions:

- FORM:

$$P_f \cong P_1 = \Phi(-\beta) \tag{16}$$

- SORM (Hohenbichler and Rackwitz, 1988):

$$P_f \cong P_2 = \Phi(-\beta)\prod_{i=1}^{n-1}(1+\Psi(\beta)\cdot\kappa_i)^{-\frac{1}{2}} \tag{17}$$

where $\Psi(\beta) = \varphi(\beta)/\Phi(\beta)$, with $\varphi(\cdot)$ and $\Phi(\cdot)$ are respectively the PDF and CDF of the standard normal distribution. β represents the minimum distance from the origin to the limit state function (equivalent to the design point) in the standard normal space, and κ_i represents the curvature of the limit state surface along each of the axes in which its canonical form is defined (a change of base in the standard normal space has to be done in general).

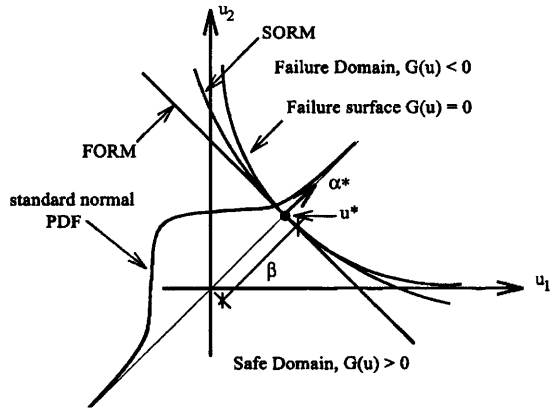


Figure 31.4. FORM and SORM approximations to the failure surface in the standard normal space [From Hamed and Bedient (1999)]

31.4.2 Simulation methods

Two of the most popular simulation methods used for reliability analyses are the Monte Carlo simulation method and the first order directional simulation method.

The Monte Carlo method uses pseudo-random number generation to sample values from the probability distributions of the random variables involved in the analysis. There are a variety of algorithms available to generate deterministic sequences of numbers that appear to be chaotic, usually based on the value of a few starting numbers or seeds (Ditlevsen and Madsen, 1996). However, a detailed description of such algorithms is outside the scope of this work.

Once a value has been sampled from the distribution of each random variable, that set of values is used to perform an analysis. This procedure is repeated, so that after a sufficiently large set of samples has been generated, a distribution of values for the computed response can be obtained. This distribution is called the simulation distribution, and the probability of failure may be obtained by integrating along the failure domain of that distribution. Alternatively, the probability of failure may be obtained as the ratio between the number of failures and the total number of iterations.

On the other hand, in the first order directional simulation method, samples are taken along a distribution of unit vectors representing directions in space. This distribution of directions is usually biased so that sampling is performed preferentially in the neighbourhood of the design point, since it is that area which has the biggest contribution to the probability of failure. For each direction chosen, the performance of the slope is assessed, and this is implemented in a simulation procedure. Finally, the probability of failure is assessed by integrating the estimated

performances for each direction, correcting for any bias in the sampling procedure.

31.5 Reliability of a parallel system

Having presented methods to compute the reliability of a single component, attention may now be focussed on a method based on a first order approximation to compute the probability of failure of a parallel system, such as the one presented in Figure 31.5. This is of interest to this problem as the failure modes were formulated to be disjointed, i.e. once the probabilities of failure corresponding to each one of the parallel systems representing the failure modes have been estimated, the probability of failure of the slope may be obtained by summation of the probabilities of failure corresponding to each one of the failure modes.

The first order approximation to the probability of failure of a parallel system can be computed using the following expression:

$$\begin{aligned} Pf(\textit{parallel system } E_j) &= P(\mathop{\mathrm{I}}_{i \in Ej} g_i(\underline{x}) \le 0) \cong F.O.approx = \ldots \\ &= \Phi_N(-b, R) \end{aligned} \tag{18}$$

In the derivation of (18), a first order approximation to the limit state surface has been used, together with other properties of the standard normal space, such as rotational symmetry.

In (18), $\boldsymbol{b}$ represents a vector that includes the values of the reliability indices for each one of the limit state functions. $\mathbf{R}$ represents the correlation matrix of the different limit state functions, defined as follows:

$$R = [\alpha_i^T \alpha_j] \tag{19}$$

where α_i is the unit vector exterior to the limit state surface i at the design point. Finally, $\Phi_N(\cdot, \cdot)$ represents the CDF of an n-dimensional vector $\mathbf{b}$ having the joint standard normal distribution with correlation matrix $\mathbf{R}$. The computation of $\Phi_N(\cdot, \cdot)$ has traditionally been a task of intense interest within the reliability community. In this work, an efficient simulation algorithm which makes use of the concept of importance sampling has been used for the purpose (Ambartzumian *et al.*, 1998). Finally, it is interesting to note that in the vector $\mathbf{b}$, the values of reliability indices obtained from the FORM analysis might be used as well as those from the SORM analyses. In such a way, the effects of curvature in the limit state function may be accounted to some point, providing a better approximation to the probability of failure even though the approximation itself is still based on the first order representation of the limit state functions presented in Figure 31.5. Both approaches have been used in this work.

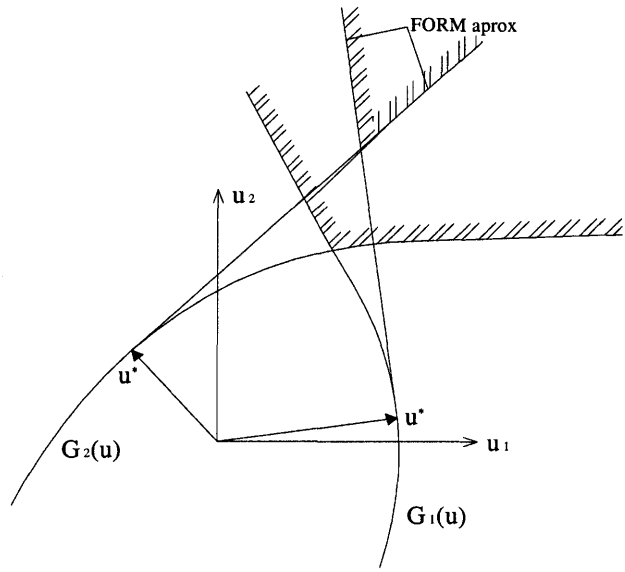


Figure 31.5. First Order approximation to the probability of failure of a parallel system

31.5.1 Simulation results

Figure 31.6 shows the results obtained with the program CALREL (Liu *et al.*, 1989) whereby the simulation methods have been applied with different levels of accuracy, as expressed by the value of the coefficient of variation in the solution required before the iteration process is halted.

The Monte Carlo simulation results have been considered to represent an 'exact' solution. It can be observed that the results obtained with the first order directional simulation method are systematically biased in comparison with the `exact' solution, indicating the effects of non linearity in the limit state functions, not taken into account when using the first order directional simulation method.

Figures 31.7 and 31.8 show the number of iterations needed to obtain a solution when using Monte Carlo simulation and first order directional simulation for certain combinations of coefficient of variation and probability of failure. It may be observed that the number of iterations required increases rapidly as the probability of failure decreases. In addition, it may be observed that the number of iterations needed to achieve the same value for the coefficient of variation in the result is about two orders of magnitude lower in the first order directional simulation method than it is in the Monte Carlo simulation method.

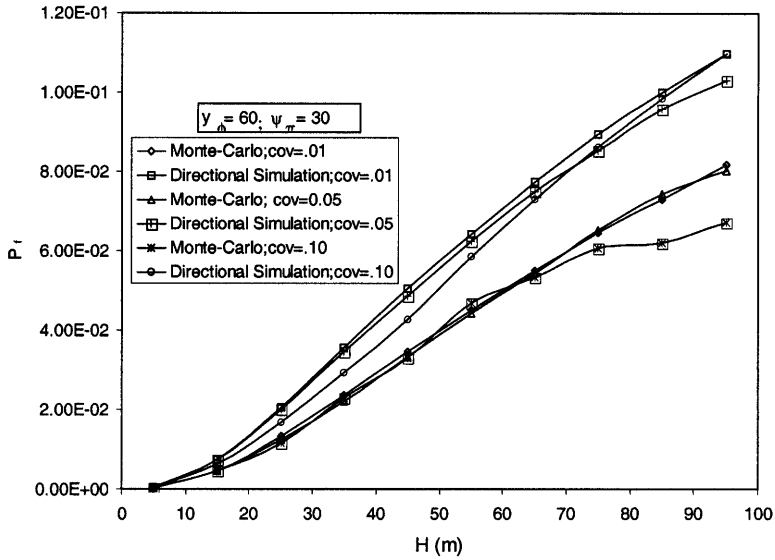


Figure 31.6. Probability of failure obtained from a number of simulation methods

31.5.2 FORM and SORM results

Table 31.2 shows some of the results obtained using the program *CALREL* (Liu *et al.*, 1989) for the limit state functions g_1, g_2 and g_3. Based on the values of the reliability index β (β_{FORM} or β_{SORM}) and the α vectors, the probability of failure of the parallel system corresponding to failure mode 1 may be computed. It may be observed that the conditions of failure of g_4 and g_5 are always verified, given the types of distributions of the random variables used in this case. The probability of failure corresponding to failure mode 2 may be obtained in the same way. The probability of failure of the slope can then be obtained by summation of the probabilities corresponding to each one of the failure modes.

Figure 31.9 shows the probability of failure of the slope obtained using the first order approximation presented in equation (18) for each of the failure modes. As mentioned before, the reliability indices obtained with FORM and SORM have been used in the **b** vector. The results obtained in both cases have been compared with those that were obtained from simulation using a coefficient of variation of 0.01. The results of the probability of failure obtained using the values of β_{FORM} practically coincide with the results obtained using the first order directional simulation method. This is because the effects of non-linearity in the limit state functions are not taken into account when using first order methods. The results obtained using the values of β_{SORM} are very close to the 'exact' solution obtained by

Monte Carlo simulation. This suggests that the effects of non-linearity in the limit state functions have been accounted for by use of values obtained from second order analysis. Even though this may not be generally the case, this suggests that it might be interesting to assess the adequacy of the method in other circumstances.

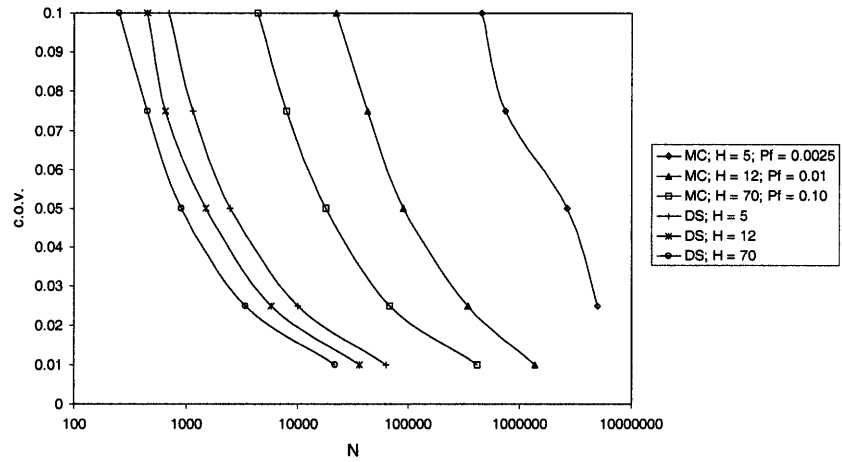


Figure 31.7. Computational efficiency of simulation methods: probability of failure vs. iterations needed (MC = Monte Carlo; DS = Directional Simulation)

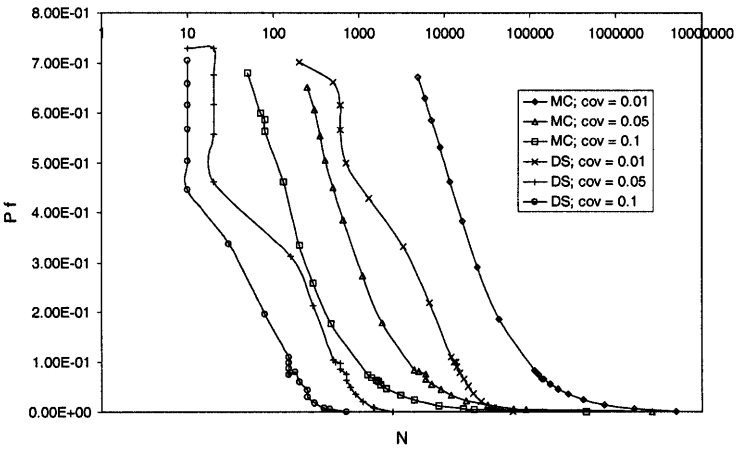


Figure 31.8. Computational efficiency of simulation methods: coefficient of variation vs. iterations needed (MC = Monte Carlo; DS = Directional Simulation)

Table 31.2. Analytical results (FORM and SORM)

L.S.F.	g1(x)			g2(x)			g3(x)		
	β FORM = -2.10071 Pf FORM = 0.9821 β SORM = -2.100725 Pf SORM = 0.9821			β FORM = 2.204909 Pf FORM = 1.37 E-2 β SORM = 2.375126 Pf SORM = 8.77 E-3			β FORM = 1.763343 Pf FORM = 3.89E-2 β SORM = 1.952363 Pf SORM = 2.54E-2		
r.v.	x*	u*	α	x*	u*	α	x*	u*	α
z	13.33	2.10	-1.00	5.7	0.126	0.0569	4.50	-0.24	-0.14
c	6.40	0.00	0.00	1.4	-1.58	-0.7181	2.26	-1.10	-0.63
f	32.50	0.00	0.00	26	-1.53	-0.6936	26.93	-1.36	-0.77

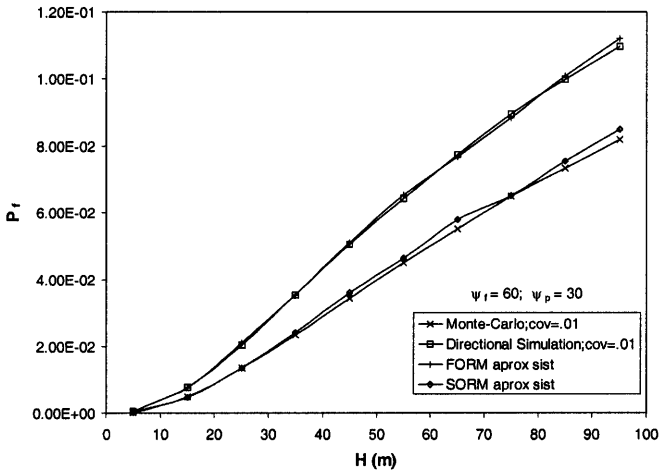


Figure 31.9. Probability of failure comparing FORM and SORM with simulation results

31.6 Conclusions

Deterministic limit equilibrium methods have been traditionally used for stability analysis of rock slopes. The stability of the slope is thereby estimated using a Factor of Safety. Such an approach cannot quantitatively take into account uncertainties that may exist in the input parameters used to model the behaviour of the slope. On the other hand, reliability methods appear to offer a promising alternative framework for managing uncertainties in both a quantitative and systematic manner, providing a logical basis for probabilistic ground characterisation.

In this work, the stability of a rock slope with respect to planar failure has been modelled by a general system formulation based on reliability, and evaluated by means of first and second order reliability methods, as well as by simulation methods.

This commences with a probabilistic characterisation of the input variables, following which Monte Carlo simulation method is used to provide an 'exact' solution, valid as long as a low coefficient of variation in the results is requested at the moment of using the method, but with the price of a loss in computational efficiency.

Analytical methods based on a first order or second order approximation (FORM or SORM) provide an alternative approach to Monte Carlo method. They are generally computationally more efficient, even though the approximations needed in the method might lead to results which differ from the `exact' solution, especially where the limit state functions present are strongly non-linear. The results obtained using a second order approximation of the limit state surface have been shown to agree quite closely with the 'exact' solution provided by the Monte Carlo simulation method. The first order directional simulation method is computationally more efficient than the Monte Carlo method, but does have similar shortcomings to the first order analytical approximations, deviating from the exact solution in cases where non-linear behaviour is present within the limit state functions.

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Part G The Way Ahead

Human societies continue to be subjected to technological advancements and change. In recent years, geoscientists have come to depend increasingly on computers and information technology (IT) to support their data collection and analysis activities. Yet the discussions at the Spa conference, as reported in this volume, emphasized that the technology itself is not the critical issue – rather, the major impediment to broader use of subsurface characterisation concerns how best to organize projects and infrastructure to maximize their utilisation.

Society increasingly expects and demands *predictions* and *judgments* from geoscientists on matters affecting socio-economic growth and health. These demands are often considered under the term 'sustainable development'. Many national geological surveys are grappling with rapid transformations resulting from their evolution from science-driven, hierarchical organizations to user-focused, project-management-based organizations.

Characterisation of the shallow subsurface exemplifies this maturing 'knowledge-management' view of the future role of the geoscience within society. The Spa conference was organized around seven major research challenges defined by Rosenbaum (*this volume*).

For example, responses to the *Representation Challenge* included how and why modelling is performed, and consideration of the circumstances which lead to a certain situation being modelled to advantage. The Total Geological History methodology (Davison, *this volume*) was proposed as one possible framework for a web-based modelling approach capable of anticipating, guiding, observing and enhancing the understanding of site conditions. Visualisation, especially of 3D models was recognized as a powerful communication tool, but one that has severe economic and utility constraints.

Responses to the *Cognition Challenge* similarly emphasized the need to avoid making the 3D modelling process a 'black box' technology to the user. Since there is a risk of misinterpreting data, there remains a question concerning who should be responsible for interpreting the data. No firm conclusions were drawn concerning the most appropriate division of responsibilities between data providers and data users.

The *Uncertainty* and *Data Challenges* promoted vigorous debates and many responses concerning appropriate technological solutions. The various sources of uncertainty were discussed, as well as various approaches to accounting for uncertainty and communicating uncertainty to clients (users). The availability, use, and dissemination of geoscientific data were recognized as important issues. Responses also considered the impact of copyright laws, problems associated the use and licensing of confidential data by public entities, and the standardisation (or lack of it) of data formats and models. When considering the archival of data, it is essential to store information about the data, or "metadata." One response was to promote adoption of the recently introduced international metadata standard for spatial data, ISO 19115.

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Responses to the *Simulation Challenge* included consideration of issues surrounding model building and methods for checking and auditing of models. Non-specialist clients may assume that the model represents the complete truth.

Responses to the *Providers* and *Users Challenges* emphasized the diversity of these two communities. Providers must understand and respond to the diverse needs and requirements of different classes of users.

The following chapter by Evans summarises the discussions on these challenges undertaken during the Spa conference. The responses provide an overview of the present situation. The majority of these challenges reflect adaptation of human and organizational resources to make more efficient use of the IT tools.

Geoscience is concerned with wealth creation (for instance finding minerals and water) and the quality of life (developing the transport infrastructure) and, increasingly, the legacy of these activities: the built environment. What is needed is information and knowledge in a form that can be assimilated and applied, for instance to urban planning and development. It is effective retrieval of pertinent information coupled with visualisation of the alternative scenarios that is being looked for, together with an awareness of potential hazards.

The computer is a servant, able to apply mathematics to a geoscientist's observations. Software can evolve, but the mathematics and the geology remain the foundation. However, it is difficult to transform a geological concept into mathematical form – an intelligent input is needed. 3D mapping software available on an affordable desktop system offers a means of achieving this.

There are two strands to the research which is now underway: (1) the technological issues of model building, and (2) the broader issues of protocol and knowledge management concerning the entire process. Both are needed and they can only be accomplished through international collaboration. This raises the issues of funding and the roles of bodies such as the IUGS and UNESCO.

There is a long term need to develop a holistic model. This is a very large undertaking, but the first steps need to be taken. Perhaps this could be started using drivers such as:

- Climate change, highlighting the concepts of the Earth as a single system;
- Standardisation of terminology to facilitate integration of information;
- Compatibility of modelling, allowing easier exchange of information and future development.

A better understanding of the subsurface conditions offers wide-ranging benefits to government, industry, and the individual. The ability to improve the urban infrastructure in a safe and cost-effective manner is fundamental to improving the environment, human and natural.

The discussion has highlighted the cross-disciplinary efforts in such areas as sustainability, and encouraged the moves towards a more user-friendly information society.

32 Current themes, issues and challenges concerning the prediction of subsurface conditions

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32.1 Challenges

Characterisation of the shallow subsurface relies on effective integration of geological information and its context. However, a range of other issues must also be addressed before any confident prediction of the subsurface can be made. These questions reflect the entire modelling procedure, from the initial collection of technical information right through to the transfer of knowledge and understanding to the end-user.

Identifying and addressing these questions is essential if the capabilities and applicability of the entire subsurface characterisation process is to adequately meet future requirements. Rosenbaum defines the main issues facing the future development of geoscience modelling and characterisation of the shallow sub-surface by relating them to seven major challenges (Rosenbaum, *this volume, and section 32.2 below*). These challenges cover a wide range of technological, societal and economic issues, from a consideration of the end-users, through what geoscientists can produce, to managing uncertainty.

Only by addressing each of these themes will it be possible to identify, and prepare for, the issues and demands that will be required of subsurface modelling in the future. Several challenges are apparent, each of which raises questions, and it is necessary to highlight these for consideration.

32.2 The Research Challenges

The seven major research challenges may be summarised as follows:

1. *The Representation Challenge*: To find ways to express the infinite complexity of the geological environment using the binary alphabet and limited capacity of a digital computer.
2. *The Cognition Challenge*: To achieve better transition between cognitive and computational representations and manipulations of geological information.

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3. *The Uncertainty Challenge*: To find ways of summarising, modelling, and visualising differences between digital representations and real phenomena.
4. *The Data Challenge*: To respond to the increasing quantity of data being collected and archived, to the increasing sophistication of the data content, and to the demands of complex analyses.
5. *The Simulation Challenge*: To create simulations in a digital computer of geological phenomena that are indistinguishable from their real counterparts.
6. *The Provider's Challenge*: The role of the geoscientist as an information provider (through the use of models) is changing, with increasing emphasis on the requirement to be customer orientated with the focus on the 'end use' of the knowledge that is being imparted.
7. *The User's Challenge*: Ensuring the end use of a material or product is made clear – to facilitate a 'performance basis' to ensure that the model is 'fit for purpose'.

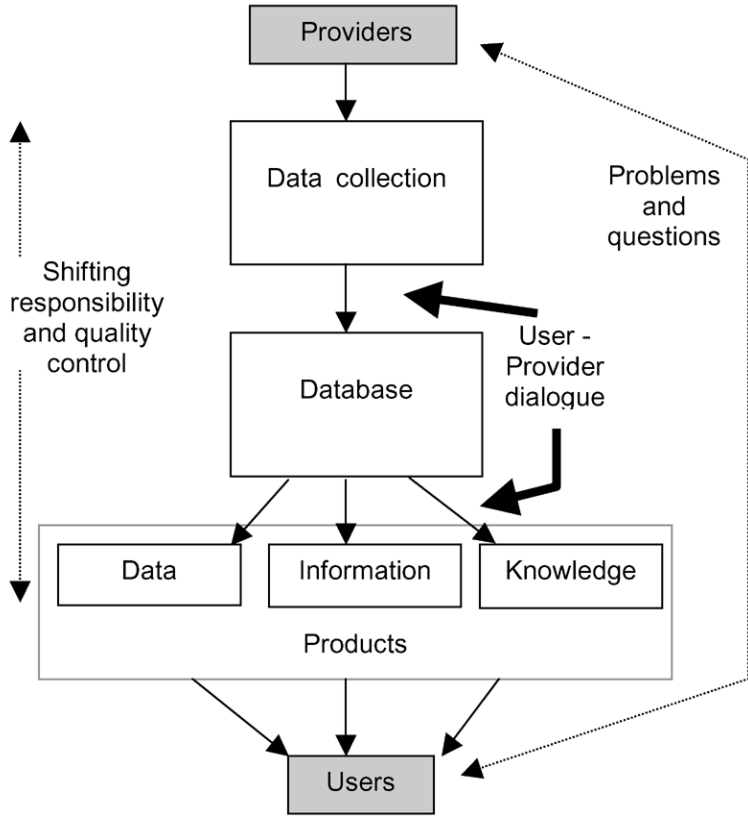

Figure 32.1. Simplified representation of the modelling process and dialogue

Although each challenge raises important questions, the relationship between the various interested parties in the modelling process currently requires the most attention (Figure 32.1). All the other issues may be successfully addressed but if the

model, or the information and knowledge that it provides, is not focussed on the problem that needs to be addressed, then the entire process is flawed.

32.3 Responses to the Representation Challenge

An important point to be considered at the outset is how and why modelling is performed, and to consider the circumstances which lead to a certain situation being modelled. For example, if one considers the case of a landslide, the question 'is a model worthwhile?' raises possible questions: is it needed to find the trigger mechanism, or to find what threshold has been crossed that might lead to failure? Is a model necessary to effect a visualisation that facilitates a safe, economic and effective design to be drawn up for the slope, enabling the appropriate limits and boundaries to be defined?

The Total Geological History methodology (Davison, *this volume*) provides a framework for a web-based modelling approach capable of anticipating, guiding, observing and enhancing the understanding of site conditions. This illustrates how, at the beginning of the modelling process, there is the need to establish the initial state of knowledge, i.e. the current state of understanding of the situation. The next stage expands the knowledge base, incorporating the user's requirements and guiding the acquisition of parameter measurements.

Visualisation is a valuable outcome, notably 3D models. However, although often used to communicate information within industry, a lot of time is required to construct them. This raises the question as to whether it is actually worth spending the resources, and to what extent does the resulting model reflect and make allowance for uncertainty. Although users usually require a relatively simple picture of the subsurface conditions, the limitations of the model in terms of boundaries to knowledge need to be appreciated. However, the users often do not have a detailed understanding of the modelled property. Indeed, concurrent demands of their profession might dictate the need for a simple 'yes' or 'no' answer to effect the decision making. A more effective activity might be to spend the time saved by not model building to increasing the user's appreciation of the ground's influence on the project!

When considering the role of the geoscientist as a provider of information, it is often not possible to place people in specific categories (e.g. provider or end-user). Distinctions between them may be vague, and many people belong to both groups, depending on the particular project.

The relationship between the provider and the user, and between the various parties involved in creation of the model, is of paramount importance. Dialogue between the parties should be developed and maintained from the outset in order to focus on the problem, and ensure that the information and knowledge from the geoscientist are presented to the user in the optimum way (Figure 32.2). Several issues exist for the end-user:

- Specifying what can and cannot be provided
- Determining cost (e.g. what is the cost of providing the required output?)

- Establishing responsibility for the delivered product
- Establishing the external sources of information and knowledge.

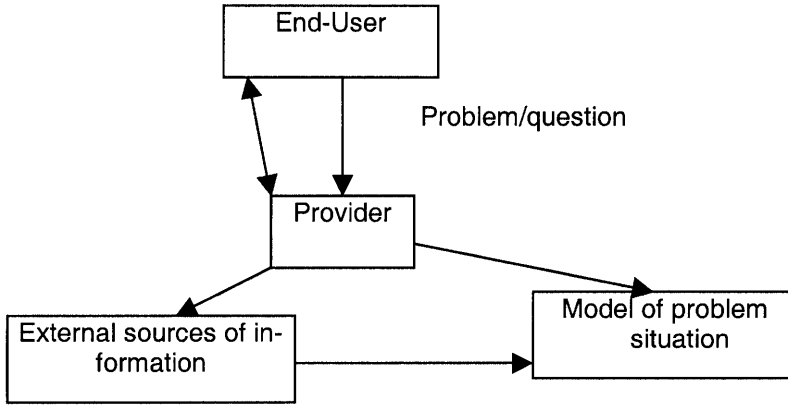

Figure 32.2. Simplified flow diagram to describe the end-user – provider relationship

Civil or geotechnical engineers often do not know a great deal about the geology of a site, and this might be the reason for not fully appreciating the utility of ground models. Nevertheless users may well have a requirement for more than a map from a model. They really want answers to questions concerning a certain site. One approach may be to create a general-purpose model, but with the ability to provide any desired special purpose information as required.

Another point is that the provider should consider the visualisation of the data, rather than immediately choosing a 3D approach. It is often better to perform modelling in 2D and then use 3D representation to help visualise and understand the data. Also it may be noted that cross-section maps might be very useful for visualisation purposes, yet not be needed for the modelling *per se*.

Modelling is viewed as a tool for interpolating and predicting the property of interest. A distinction should be made between interpretation and interpolation.

Sometimes the question is raised as to whether GIS with a 3D capability provides a better form of representation than CAD. However, it should be noted that technology is not the issue, but rather what the user requires. On a similar theme, a closed system may be sufficient for one end-user but not for another user who requires an open system with access to the raw data.

The way that a model is presented can be very important, because different users of the same information, or even the same model, may require different ways of presenting the information. Some users, insurers for example, may require a 'number' representing land or property value, whereas other users may want to know whether planning permission should be granted or not, but not necessarily be interested in why.

There is a danger of modern computer graphics hiding 'real data'. Whereas a simple presentation approach can be appealing, especially if the amount of data collected is large, there is the need on occasion to reveal the source measurements. Sometimes, there can be a danger of being impressed by the visual output of a model, and therefore forgetting what is actually trying to be achieved.

32.4 Responses to the Cognition Challenge

Information relating to the subsurface does not always provide the kind of answer that is expected. A difficulty arises from the user having little knowledge of the processes that have been followed to arrive at the answer. To the user, the whole modelling process appears rather as a 'black box' technology, i.e. an answer is provided, but there is no audit trail to show how that answer has been reached. Consequently this situation raises a rather important question: does information technology provide a better solution than can the human brain when dealing with ground information? Current geoscience models may look impressive but do not necessarily provide any new information, merely make it more accessible.

3D modelling is not necessarily the final goal for prediction of subsurface conditions, but may be used as input for further physical modelling. The aim is more likely to focus on the use of the computer software to yield geological meaning from the model. From the geological point of view, the real laws of nature are not totally understood, but hypotheses can be produced using models, and modelling can be used to forecast future events.

The focus should be on the concept of how the natural environment works, so the 'real' geology in the field still remains the first and the main step in the ground characterisation process.

Although the modelling process involves a long line of activities, it is important to understand how the software works (i.e. not just to have a 'black box' which produces images that look impressive).

32.4.1 Responsibility for interpretation

A question arises as to whether it should be the end-user or the provider of the model that should be responsible for interpreting the information presented. Although the end-user is at liberty to use the information in a manner they see fit, there is also a responsibly with the model provider to assess the quality and ensure the validity is made clear. There is divided opinion concerning where the division of such responsibilities should lie, and no firm conclusions can yet be drawn.

One solution is to adopt a probabilistic approach, placing the responsibility with the end user who assigns the product a numerical magnitude of risk or a level of uncertainty. A problem with this approach is that some clients may well not employ personnel with the knowledge of how to make such assignments, nor subsequently how to use such values to make such decisions.

It is commonly felt that the client should solely be concerned with making the decisions affecting the project. Thus the provider should refrain from making decisions on behalf of the user, and should just deliver the information demanded in the contract. However, offering advice is a quite different matter to making the decision.

Whichever approach is adopted, the end-point must be made clear from the beginning and all uncertainties and assumptions should be systematically recorded. The modeller needs to keep in mind the knowledge level of the client, in particular advising as appropriate if there is doubt that what the client wants is what he needs. The client should be kept fully informed and there may be a need for educating and training.

Since there is a risk of misinterpreting data, there is an issue relating to who is responsible for interpreting the data. In some countries, when the national geological survey provides the data, it is the practice to clearly state that the only 'known' data occur at specifically sampled data points; everything in between is an interpretation based on these points. In the Netherlands, the government survey (TNO-NITG) is only responsible if there are actual errors in the data, not if there are errors in the interpretation.

32.4.2 The role of a geoscientist

A conflict exists concerning the philosophies of the different interested parties involved with ground investigations. The general issue of conducting research for preventative measures, as opposed to a purely reactionary approach to tackling problems once they have arisen, requires consideration. The geoscience community generally believes that it is best to spend a certain amount of time and money on investigating any potential problem before damage to the environment or human health arises. But some in the non-scientific community argue that such funds would be better spent in other ways, and that it is better to react to a problem once it has arisen rather than spend money on pre-empting a problem that has not yet actually occurred. However, current geoscience practice regards it to be a better option, and more common sense, to invest money in prevention and forecasting than just curing problems after they have occurred.

It thus becomes the task of the geoscience modeller to extract the appropriate information to answer the question that is posed. Any non-specific character of the questions should be reduced as much as possible. Advice given by the provider should, wherever possible, be based on a financial approach (e.g. 'yes, a house can be built at this site, but from an economic point of view it would be very expensive'); financial issues tend to form the main basis for decision making amongst users.

Society in general tends to be unaware of the benefits that accrue from understanding the natural environment. Geoscientists (e.g. model providers, geological mappers, surveyors) should establish a view of what society needs and work towards satisfying that need. This implies a requirement for education, illustrating to society what it is that is needed and how this can be of benefit.

An example concerns the deep underground storage of toxic waste. There is currently little work in progress on this topic. However, deep storage of waste will inevitably become a requirement. Allowing expertise to lapse is likely to mean that knowledge in this field will have to be acquired from scratch, which will be extremely expensive. Thus, while there is no immediate financial benefit or requirement for such research in the near future, it will become a relevant issue as time goes on and a better solution will be obtained, at cheaper overall cost, by maintaining the funded effort.

There are several possible ways whereby the geoscience community can link with society, through the national geological surveys, learned societies, local and regional government, as well as the media.

32.5 Responses to the Uncertainty Challenge

At the start of a project it should be agreed upon which questions need to be answered, and which data should be collected. The quality of the data should depend on the risk that the client is willing to take.

Uncertainty will be present, and its magnitude has to be balanced against the cost of reducing it.

When attempting to predict subsurface conditions, the geoscientist must consider two distinct areas of uncertainty:

- The uncertainty in the data and measurements themselves,
- The uncertainty in the modelling processes (i.e. the mathematical simulations and equations used to simulate real world processes).

In resolving and defining these sources of uncertainty, three principal questions must be addressed:

- Who needs to know the measure of uncertainty?
- Why is uncertainty being measured?
- What are the confidence limits?

Uncertainty has different implications in different situations, and must be treated in a case dependent manner. Uncertainty with respect to hazards is obviously more important in an urban environment than an uninhabited rural area. A sensitive approach to the vulnerability of the area can be taken into account. It should be noted, however, that not all the uncertainties are necessarily important; there is a need to establish which are the ones of greatest interest, and focus attention accordingly.

Conceptual models are an alternative option, but these are rarely considered to be good enough, perhaps because of a perception of imprecision. Simplifications will inevitably be required, as is a consideration of the consequences should the assumptions be wrong.

Whichever approach is adopted, the models have to be sufficiently good to answer the questions posed, but there is not necessarily a need for overly complicated models. In some cases qualitative answers will be good enough, depending on the risks that the client is willing to accept.

32.5.1 Uncertainties in the Data

Uncertainty concerns the quality of the model that is built. However, the very nature of uncertainty means that it is not possible to tell how accurate a specific scenario will be. In any case, the accuracy of the final result is going to be no better than that of the input data. Error propagation, which looks at how the error is carried through the modelling process, is one of the issues that must be considered.

Uncertainties in data can usually be quantified, and accounted for in models. Quantification is not always simple, and prone to human influence (bias).

There is a risk associated with trying to obtain less uncertain data. Additional site investigation will provide more and better data, but at significantly greater cost.

One option is to use probability, representing uncertainty and risk as a 'factor of safety', a commonly used approach by engineers. Probabilistic methods may appear to be accessible to non-technical users, but the question exists as to whether engineers know how to actually use the probabilities so obtained.

The relevance of 'sensitivity analysis' should also be considered. It is important to know which parameters of the system are most influential on the model behaviour, and thus which parameters have to be determined as a priority.

32.5.2 Uncertainties in the Modelling

A common criticism of modelling is that there is no indication of uncertainty, thus the user might reasonably deduce that all the information portrayed is accurate and certain in value. The twin issues of uncertainty and probability of risk exist must be considered in the modelling process, stated in the model products, and made clear to the user.

Several possible approaches could be utilised. Monte-Carlo simulation is a widely used technique, but this approach does have the drawback that users may not feel comfortable with uncertainty being presented alongside the results. The desire is somewhat contradictory to what has just been considered: to provide an exact solution rather than a likely solution with confidence bands!

Many models make use of geological expertise, but this is rarely reproducible. This raises the issue of how to quantify uncertainties in expert knowledge. Geologists often make use of fuzzy logic rules when making decisions; geological knowledge and such rules are not formalised.

Uncertainty can arise from several different sources. Many factors have to be addressed, including issues such as the time period considered. It may be the case that, for a particular study, the modelling is conducted over too short a time scale to gain a full understanding of the situation.

Scales have to be considered in both temporal and spatial terms during the collection, modelling and interpreting of data. One example of the importance of the scale of properties is provided by the use of maps. Geological boundaries are uncertain, and this may not be reflected in the published map. Also, when considering scales of parameters, if different scales are used for different maps, resolution of data can become a problem.

Presenting outputs from a model should take the approach of finding several possible alternatives, where appropriate, rather than one single answer. A degree of uncertainty will always be present when considering subsurface conditions, and the user should accept that there will be a margin of error – no model will be 'perfect'.

In the future, it is a possibility that different models describing the same situation may be pitted against each other to argue a specific case, as has been done with geostatistics applied to ore reserve calculation.

32.5.3 Communicating Uncertainty

The topics of risk definition and communication of the risk are important. They include related issues such as risk awareness and cultural aspects. There is also the need to decide whether a given uncertainty range is acceptable, or too high. Geoscientists therefore need to consider how they are to convince the end-users that their product is useful and how to interpret the information provided.

It will often be the case in geoscience that when data is obtained from different sources, different model results might be produced. It is therefore desirable that the geoscientist states what is known about a model, the data and the processes, and thus be able to inform the client as to the real status of the model being applied to the problem being addressed. Thus, instead of giving a single value for the error of estimation, it would be better to provide a range of uncertainty. The essence of the approach is to utilise statistics. Thus different models of a certain situation can be formulated and a (statistical) possible outcome derived (but not *the only* outcome).

3D models and visualisations should be able to provide tools for exploring uncertainty, and to assist in finding it, understanding it, mapping it and visualising it. This provides a distinct advantage for developing 3D modelling as a tool of choice for ground characterisation. Another approach is to employ visualisation, expressing the uncertainty as a 'fogged' display making clear the lack of precision. This would be analogous to the way a geologist would use a dotted line on a map rather than a solid boundary to represent the uncertainty of location.

But it is not just the technique that needs to be addressed. Geoscientists do not work according to formalised rules, and this raises the question of whether there should be an attempt to define such formalised rules. Geoscientists make their 'own' maps, which means there is a lot of subjectivity involved. Attempts to reduce this individual subjectivity may produce better models, but at the expense of incorporating full geological judgement. Geoscientists with different backgrounds (e.g. geologists, geomorphologists, geophysicists) may each produce an entirely different map of the same area, from the same data. The same problem might even

be encountered when people from the same disciplines are independently describing the same borehole. A solution for the latter case is 'team calibration'. However, a good quality assurance system is required for this to succeed.

32.5.4 Time and scaling

It is difficult to quantify how the ground evolves, for example to establish why a slope fails. Uncertainty can arise from several different sources. Many factors have to be addressed, including issues such as the time period considered. It may be the case that, for a particular study, the modelling is conducted over too short a time scale to gain a full understanding of the situation.

The scale of parameters used in modelling is also crucial. Scales have to be considered for many parameters, in both temporal and spatial terms, and also for the collection, modelling and interpreting of data. One example of the importance of the scale of properties is provided by the use of maps. Geological boundaries are uncertain, and this may not be reflected in the published map. Also, when considering scales of parameters, if different scales are used for different maps, resolution of data can become a problem.

Presenting outputs from a model should take the approach of finding several possible alternatives, where appropriate, rather than one single answer. A degree of uncertainty will always be present when considering subsurface conditions, and the user should accept that there will be a margin of error – no model will be 'perfect'.

In the future, it is a possibility that different models describing the same situation may be pitted against each other to argue a specific case, as has been done with geostatistics applied to ore reserve calculation.

32.6 Responses to the Data Challenge

The availability of geoscientific data is an important issue. National geological surveys have an important role to play in collating archival information. An efficient cataloguing system is essential to facilitate access to their extensive holdings of geoscientific data.

The large amounts of data in the national geological survey archives may sometimes obviate the incorporation of historical information. Unfortunately, some 'legacy systems' holding important historical data employ non-standard or obsolete methods to record the information, a particular problem if these are not accessible through the Web. Several national geological surveys are investing considerable effort in modernising and standardising their legacy data banks.

Situations can also arise where private data are stored by the geological survey but cannot be redistributed, for instance if obtained commercially or for a sensitive project. A compromise may exist whereby a certain time limit can be imposed before release of the data to the public is authorised. The geological survey of each country is best placed to take on this task.

32.6.1 Data storage

Not all types of data can fit into a relational database system. This raises issues of how to store the data, transfer it and manage it. The kinds of data structure needed to support the data also needs to be considered, and how to make it available to different users and applications.

It should always be specified why data are collected, and their reliability and applicability for different kind of models should be recognised. The conceptual model has to be able to communicate with the data. The same data are often used for entirely different purposes. However, the geoscientist always needs to be aware of the problem of data-misuse.

The technology for creating 3D images in GIS is not the barrier to progress, but rather obtaining the appropriate information required to create the object. There currently exists some concern at the large gap between available modelling technology and the ability to collect good data for the models. This situation may lead to using a model with very little data and which is therefore inappropriate for solving the problem. Clearly, it is important to continue conducting relevant field work and not rely purely on a theoretical model.

An important point to be considered concerns the IT infrastructure and management of the entire modelling process. The IT infrastructure (both hardware and software) has to support the complete workflow. Hardware and software infrastructure should be thought of as a kind of 'umbrella' covering all challenges that exists within the modelling process.

32.6.2 Data dissemination

Elsewhere in this book issues concerning dissemination of geoscience data are considered (see chapters by de Mulder and Kooijman, and also Groot and Kosters). There are several societal implications to the dissemination of geoscience information/data, and controversy about appropriate methods of funding data dissemination.

Should a user have to pay again if the geological survey is a government body (and thus funded by taxation)? Should meta-data be freely available? Should there be free access to baseline data, but payment required for more detailed data? How should the needs of the 'thick' client (much data detail and flexibility, relatively few users), and the 'thin' client (small amounts of interpreted data and information, relatively numerous users) be addressed? Different practices exist in different countries regarding data distribution. These different practices lead to different methods for funding the data acquisition and storage. For example, there is a balance between releasing data freely and making money from advice and consultancy (i.e. data is free; knowledge is for sale).

The role of the geological survey continues to evolve, but the past tendency to do work funded by the government primarily to further geoscience knowledge is being overtaken by an end-user focus.

Copyright laws pose problems for dissemination of data. In the UK, for example, paper documents can be copied, within reason, for teaching purposes, but

electronic data cannot be copied. The issues relating to copyright and intellectual property rights must be addressed further.

Of course, it is not only the national geological surveys which can provide a dissemination service for geoscientific data. Perhaps educational institutions have a role, through the Internet.

32.6.3 Standardisation of data formats and models

Within geoscience there is a lack of standardisation concerning the format of data, making modelling difficult. A possible solution would be the development of a software tool whereby the field geologist can load their information as it is collected, transmitting it to a networked database and rapidly making it available for modelling. Such a device does not necessarily have to be portable, but rather a piece of software at base that can easily capture and transmit the data in a standard format.

There is the associated need to agree upon a hierarchy of definitions for use in databases employed by the different geological agencies, just as there have been agreements in the past for paper maps. A major question is how to use these hierarchies in a relational database management environment.

There is a further issue arising from the dissimilar terminology and classifications used by the various geoscientific disciplines. Words can have different meanings or interpretations, and a way of preventing this needs to be derived. For example, should standards be defined for both data and data description?

The ultimate standardisation of all data descriptions may be beyond reach, because there will always be problems arising from different disciplines giving different interpretations and results, and of course the issue of language.

32.6.4 Importance of providing metadata

When considering the storage of data, it is not only the data itself that should be stored; it is also essential to store information about the data as well. This is called 'metadata' because it is 'data about the data'. Metadata will provide information concerning, for example, data quality, details of calibration, and any subsequent processing. Data alone, without the metadata , is essentially worthless. A new international metadata standard for spatial data, ISO 19115, has recently been introduced. The ISO 19115 standard reflects extended experiences with several national standards related to spatial data.

The format of metadata can vary depending on the data it relates to and the situations specific to that data, but the basic principle remains the same: define the characteristics that are important to the user.

Metadata define data quality, and thus will assist in the quantification of uncertainties, for instance when data are used in the modelling process or reported to the end-user. It is important to maintain data quality, not just data quantity.

32.7 Responses to the Simulation Challenge

Several issues arise when interpolating between sampled data points. This can be achieved by triangulation (TIN) or by applying a regular (raster) grid. There are many different shapes of grid that can be used for modelling, but it is difficult to mesh the ground to the grid. The triangulation grid offers greater flexibility than the cubic grid, and perhaps is the way forward for mechanical modelling and flow modelling. Another technique is to apply a hexagonal shaped grid. This shape can be adapted to the geometry with greater ease.

However, the interface between 2D and 3D models is generally not very good. Concerning flow models, there are generally two kinds, each having particular problems:

- Homogeneous: the main problem is of vertical scaling, generally scaling up the properties
- Heterogeneous: boundary conditions are important but the main problem is believed to be ascertaining for describing physical parameters to describe multiphase flow. Once this has been achieved, it is thought that more efficient models can be established.

New theoretical work in up-scaling is required, particularly when considering fractured media. However, understanding the processes is perhaps more important than developing even more advanced models. An understanding of the geometry of fractures is required. Fault zones are particularly difficult to model and current models are often oversimplified. Models are generally based on layers, but the model really needs to deal with a set of different objects. An outstanding issue is how to present box cell and boundary objects together.

Often there is data that has been selectively excluded, so that the model can be kept relatively simple. For example:

- The precision of the data is generally not discussed
- The errors are not given
- Groundwater fluctuations are overlooked
- Time is not included
- On-going processes are not considered.

32.7.1 Auditing and checking models

Checking and auditing of models, and the way that these are conducted, are important issues. Questions arise as to how to quantify models, and sometimes there is also a need to demonstrate how models might be wrong. The ground is complex; models are relatively simple. Non-specialists are thus at risk of assuming that the model, and the information provided by the model, is representing the

complete truth. Hence there is a requirement for the provider to indicate what the model can and cannot achieve.

Referencing and cross-validation of data is an important component of quality assurance, but standards are only at an early stage of being defined (e.g. Eurocode 7), and benchmarking for data handling is only prevalent in related fields such as the oil industry. In general, the quality control of data within the geoscience profession is rather poor. This is in part because organisations and individuals are tending to develop their own standards in the absence of agreed standard procedures. Unlike many other fields of scientific study, standard reference data sets are not available to test and compare the quality of geoscience models. It may be noted that the Internet should in future assist facilitate such exchange.

Validation of the model itself is another important and sometimes overlooked issue. Consideration should be given to checking the models, at least empirically, to verify that it simulates reality. Whether a particular model has been validated is often not made clear. However, it should be noted that models do not represent static situations, but dynamic ones, and so should, ideally, be reassessed every few years.

The development of verification tools to enable validation of models is one of the challenges facing modellers. It may be noted that inverse modelling and sensitivity analysis are of growing importance.

32.7.2 Simulation of reality

Another challenge faced by geoscience modellers is to try to create simulations of geological phenomena as a basis for prediction and assessment of alternative scenarios. Using digital computer visualisation technology, such models may appear to be indistinguishable from the real subsurface situation. However, it is actually impossible to simulate reality to such an accurate degree and the accuracy may well be deceptive. The simulation of reality can only be achieved by attempting to provide a simplification, and therefore the goal should be to provide a model which is as indistinguishable as is practicable for the given situation.

The geological environment is a very complex setting, and it is a challenge to try and represent this complexity with the limited capacity of modelling tools currently available. Even to adequately combine, and express, parameter properties and parameter uncertainties associated with a digital terrain model is a difficult task.

A challenge exists as to how to simplify the real world to obtain a representative geological model. Geoscientists still need to distil that information which is the essence needed to represent the real world, aligning the project objectives with the modelling requirements.

An issue exists concerning process-based modelling, and the question of whether it is possible to sufficiently quantify geological processes: are the models good enough? Process-based modelling is a challenge, and there is a long way to go before geological processes are understood sufficiently to advance this approach. However, it must be remembered that there is a certain amount of uncertainty incorporated in any model, from either the data itself or from knowledge of

the modelling processes. A pragmatic approach is needed, recognising that the results of a model should not be regarded as a 'photograph' of reality.

32.8 Responses to the Provider's Challenge

There is an urgent need for the providers to recognise that the onus is on them to indicate the degree of uncertainty concerning the models, and to avoid overstating what the model can achieve. The providers' challenge is to reduce the risk and cost throughout the entire modelling process, from data collection, processing and interpretation through to the application of the end product by the user.

32.8.1 What can geoscience produce?

The outputs that the geoscience community can produce may be categorised as:

- Data – measurements of parameters
- Information – objects based on data but presented within their context
- Knowledge base – judgement and interpretation based on information

Visualisation is then needed to communicate these outputs, a question to be faced being whether to present the results from such models in 2D or 3D. The answer needs to consider if the provider is working towards the product that the end user wants, in a form that is acceptable. However, products such as 3D seismic sections and borehole logs may not, on their own, satisfy the end-user. There is a need to take care not to selectively pass on the knowledge that has been acquired, whilst handing over the tools to manage and extract what is needed.

32.8.2 Incorporating knowledge within the model

Data, information and knowledge are three distinct concepts, and they are understood and used differently:

- Data is available for any discipline to use
- Information depends on the environment (context)
- Knowledge may be quite abstruse.

It may well, therefore, be necessary to incorporate experience and knowledge within an expert system (ES) to make it accessible, not only to the end-user but also to a decision support system (DSS) that may subsequently be employed. An example of the problem to be faced is given by geological strata; some layers are older than others and will only occur in certain relational situations. But how can the computer be 'taught' to know this?

One approach is to assign 'weights' to factors to indicate their sequence or degree of importance within the model.

Some objects are observed and some are based on indirect information. Another option is to code objects to indicate their knowledge representation.

A further issue is how to capture, in the model, the geologist's ability to interpret the data. It may be possible to do this, but in reality there is a resource issue concerning the amount of time and money needed to develop such a system. The geologist may be the most cost effective solution!

Complex projects will require communication between a number of modellers, as well as between the users and providers. This issue is particularly relevant to international teams and the likelihood of splitting the tasks required to create the model. The Internet is facilitating this method of working.

32.8.3 New techniques

New techniques and protocols are being developed and duly considered for modelling purposes.

There is a danger that data which does not fit tends to be ignored. However, it is important that such data are not dismissed without due consideration, and it may turn out to be the most important factor.

A model is of necessity an evolutionary phenomenon, dependant upon the specific fields of expertise brought to bear on the problem. Many disciplines rely heavily on models, regarded as essential for prediction and understanding certain situations, especially concerning economics. However, in social science, general models are often considered to be unhelpful and this raises the point of whether some models used ever really fit in the first place, and whether they are indeed helpful.

Geological models tend to have very complex parameters, and require a high level of understanding to take into account the significance of the data. Relatively new techniques for gathering sub-surface information (e.g. ground penetrating radar) are becoming more widely used, and provide different information than could be previously obtained. However, this does not mean that 'old' methods should be disregarded. The sophistication of a technique, whether it be for data gathering or data processing, can be important, but it is the interpretation of the data that is of greater consequence. Data collection techniques and processing methods are significant. It is often the case that obtaining the appropriate quantity of data is not the issue, the problem lying with how the data is actually used. Also, when considering the accuracy of data input versus the interpretative output, a key factor is how the data was selected.

32.9 Responses to the User's Challenge

A typical list of end-users of ground characterisation models would include:

- Property developers
- Land use planners
- Insurance companies
- The agricultural industry
- Energy producers
- The oil industry
- Mineral extractors
- Waste managers
- Civil engineers
- The construction industry
- Consultants
- Telecommunications organisations
- Water companies
- Other utility companies
- Government agencies
- Emergency preparation offices / Disaster relief agencies
- Military / defence organisations
- Municipalities / local authorities
- National parks
- Environmental protection agencies
- Educational establishments
- Geoscientists
- The general public

The (end) user may not always be known, or may change in time, and often is not a geoscientist or have a geoscientific background. Geoscientists (as well as users) should be aware of the notion of 'thick' and 'thin' clients (Turner, *this volume)*: 'thick' clients are sophisticated users who desire a wide variety of data and information from a varied, very rich data/information stream, whilst 'thin' clients desire a relatively simple, concise answer from a small amount of carefully selected data. Thin clients are numerous, and include the general public, whilst thick clients are less numerous but are more likely to employ their own geoscientific expertise. Also, the user of an intermediate (geoscientific) product could simultaneously be the provider of the next product.

Different end users have different needs. The scope of interest of the users, and their capacity to use geoscience data, should be determined in order that they can be offered information in usable form. There is a need for the geoscientist to facilitate communications with the end user, identifying what the user requires rather than what the geoscientist thinks they want: these may be quite different. Dialogue is thus the key for effective delivery, and necessary for maximising use of the information.

It is necessary that one discipline should be prepared to listen to another. It may well be possible to learn from modelling advances made in other areas, for instance in medical science. It also has to be remembered that the technology is not necessarily the limiting factor, the problem may lie with building the model.

The user should normally trigger the project; the user's requirements, available skills and questions posed can then define what data should be gathered, the way it needs to be interpreted and presented. However, the user requirements are often not well defined but, as stated above, this may be just a communication problem, rather than a technical problem. Many users do not know how to use the information they are supplied with, so the production of geological and geotechnical reports should allow for this, written so that they are understandable to the user and not overly complex, i.e. restrain the provision of unnecessary information and intermediate products.

As well as dialogue between the parties, there needs to be productive communication between all participants concerned with the modelling process. However, it is not uncommon for there to be a 'lack of understanding' between, for example, geologists and engineers. Geologists tend to think conceptually and favour a descriptive approach to handling problems and situations, utilising judgement. In contrast, engineers tend to adopt a quantitative, deterministic approach. Engineering geology has developed at the interface and attempts to bridge this gap.

32.10 Geo-education

There are several issues concerning the future of education within the geological sciences, particularly with regard to teaching and learning and to the academic advancement of the discipline.

One issue is whether the focus should be on teaching 'traditional' geological topics or to devoting more time to teaching computing techniques, even though the latter continue to evolve apace. There are time constraints, but where is the line to be drawn between education and training? This argument may be extended to the attention that is needed to learning how to participate in team work as opposed to individual study and attainment of traditional academic goals. Assessment methods strongly favour the latter, constrained by the accreditation demands of the professional institutions.

Another issue concerns whether it is indeed possible for higher education to proceed without a strong research base and without active engagement of academic staff in the development of the profession. National government funding policies are having a profound affect on the ability of universities to deliver the teaching and learning environment appropriate to the needs of industry and professional development.

32.11 Conclusions

Consideration has been given to the whole process of characterising the ground, from information needs to modelling. The outcome is not just the production of another bit of information, but a contribution to knowledge. There needs to be an appraisal of provider capabilities, user needs, the provider-user interaction, the

means by which data is collected, processed and stored, and the determination of uncertainties that exist at different stages of the modelling process. In the following (final) chapter, Turner and Rosenbaum propose a research agenda that aims to promote these appraisals and outcomes. They also discuss how the formation of European and international research networks might assist in these endeavours.

The one topic that, perhaps, currently requires most attention is the relationship between the various interested parties in the modelling process. All of the existing and future issues may be successfully addressed but, if the model, or information and knowledge, that is provided is not focussed on the problem that needs to be addressed, then the entire process is flawed.

The relationship between the provider and the user, and between the various parties involved in creation of the model, is of paramount importance. Dialogue between the parties should be developed and maintained from the outset in order to focus on the problem, and ensure that the information and knowledge from the geoscientist are presented to the user in the optimum way.

Acknowledgements

The information presented in this chapter summarises the programmed discussions that occurred during the Spa conference in July 2001. This has drawn extensively on the opinions expressed by delegates, only made possible by the pervasive enthusiasm and willingness to participate. They reflect the opinions of geoscience professionals from a wide range of disciplines, backgrounds and experience. These are too numerous to acknowledge individually, but all the delegates at the conference are named at the end of this book.

Particular thanks are owed to the rapporteurs who recorded the main points and ideas raised during discussion sessions: Paulo Lopes de Figueiredo Coelho (Universidade de Coimbra, Portugal), Lluis Barcons Comellas (ITC, Netherlands), Mariagrazia d'Emilio (Università degli Studi della Basilicata, Italy), Gerald Gabriel (Institut für Geowissenschaftliche Gemeinschaftsaufgaben, Germany), Rebecca Gay (Imperial College, UK), José Duarte Grazina (University of Coimbra, Portugal), Pirjo Hellä (Fintact Ltd., Finland), Rafael Jimenez-Rodriguez (Universidad de Granada, Spain), Milda Kairyte (Göteborg University, Sweden), Villy Kontogianni (University of Patras, Greece), Blanca Perez Lapeña (ITC, The Netherlands), Dimitra Nika (National Technical University of Athens, Greece), Jenny Norrman (Swedish Geotechnical Institute, Sweden), Anna Papazisi (Aristotle University of Thessaloniki), Jane Poole (Symonds Group Ltd., UK), Chris Taylor (Nottingham Trent University, UK), Robert Vuurens (TU Delft, the Netherlands), Brecht Wassing (Netherlands Institute of Applied Geosciences), Anna Zervopoulou (Aristotle University of Thessaloniki, Greece).

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Turner AK, Rosenbaum MS (2003) The Global Geoscientific Knowledge Network: overcoming the impediments to subsurface characterisation *[Chapter 33, this volume]*

33 The Global Geoscientific Knowledge Network: overcoming the impediments to subsurface characterisation

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33.1 Introduction

In recent years, geoscientists have come to depend more and more on computers and information technology (IT) to support their data collection and analysis activities. In this regard the rapid evolution of IT in the 1990's made the computer on the geologist's desktop an increasingly important, powerful, and economical analysis tool (Figure 33.1).

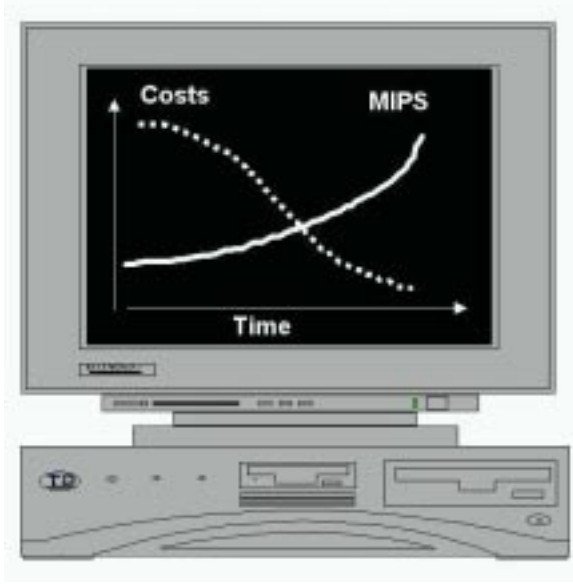

Figure 33.1. The impact of technological advances over the past decade

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Yet a dichotomy exists between Geosciences and IT. While many geoscientists have embraced IT concepts and applied IT tools to enhance their research, a much larger number of geoscientists have not. They may use computers to prepare documents and to communicate with colleagues, but have largely ignored the potential uses of IT to directly support scientific studies. Loudon (2000, page A131) eloquently describes this existing dichotomy:

"Like a canal navigator watching an iron horse steam by, like a railroad engineer sighting a horseless carriage, the geologist viewing images on a computer screen is witness to a paradigm shift. Unrecognised assumptions lose their validity, and things will never be the same again. The electronic tools now fashioning the geoscience knowledge base open a door to the unknown."

"But look away from the screen, step outside the door, and little is altered. The geoscience community is split. For most, there has been no revolution; the case for change has still to be made. Those captivated by new technology have set their own agenda, and largely been ignored by the traditional practitioners who take for granted their pens, paper, and printing press."

We, the organisers of this Spa conference, subscribe to these sentiments. We organised the conference not merely to provide a forum that encouraged dialog among those geoscientists who were adopting the IT tools, but also to establish a network for supporting future broader applications of these technologies. We were, and are, convinced that the time for establishing such a network has arrived.

Yet the widespread adoption and successful use of new information technologies to improve subsurface investigations depend on accurately identifying user requirements, and also assessing the associated technological, social, economic, and policy issues. The issues surrounding the identification of user requirements have been addressed previously (Turner, Chapter 5, *this volume*) and so will not be repeated here. Plans for future directions must account for current technological and socio-economic challenges. These are discussed in the following sections.

33.2 The role of technological innovation

Human societies are continuously subjected to technological advancements and change. The rates of change are variable, but change is inevitable and requires modifications within society. On July 13, 1999 newspapers reported the termination of commercial Morse wireless telegraphy in North America. On the previous day the last commercial station located just south of San Francisco on the California coast had sent its last messages to ships at sea and shut down. Although Morse telegraphy continues in other parts of the world, the professional Morse telegraph operator is no longer part of North American society.

Geology developed during the industrial revolution when rapidly growing consumption of various resources demanded vigorous world-wide exploration. During this period of rapid technological advances, the geosciences, for the most part, remained relatively immune from change. Methods of conducting field observations, recording these observations, performing analyses and syntheses of this information, and producing maps and reports became well-defined and standardised

procedures. For example, present-day geologists can immediately relate to the activities shown in Figure 33.2 (Rabbitt, 1989), although dress codes have changed considerably.

Figure 33.2. Gentlemen engaged in geological pursuits, 1836. [source: U.S. Geological Survey Circular 1050, Rabbitt (1989)]

The introduction and adoption of a new technology follows a predictable pattern over time that can be described by a "technological acceptance curve" (Figure 33.3). The perceived value of a new technology when it is first invented is quite low, but this value increases as the new technology gains acceptance. It remains relatively high and stable during a period of widespread use when it is the generally accepted "best-practice" or "usual method" of doing things. Most technologies ultimately experience obsolescence and slowly decline in perceived value as they are supplanted by newer technologies.

As shown in Figure 33.4, technological innovation can be represented by a sequence of technological acceptance curves. Newer technologies replace older ones only when clear benefits can be seen. Even then, the change from one technology to another is not universal – some individuals quickly adopt the new technology while others continue with older methods. Figure 33.4 also illustrates that newer technologies generally increase levels of perceived value. This increased value may result from several factors – the new technology may provide greater efficiency and thus economic benefits, or it may provide time-savings (also an economic benefit) or it may improve product quality.

The most powerful impetus for adopting new technology occurs when it provides new capability. In many cases, adoption of new IT tools by geoscientists allows them to undertake investigations or research that was previously "impossible." Thus, in spite of the existing dichotomy discussed earlier, we believe that IT

in general, and 3D subsurface characterisation in particular, will provide a new geoscience paradigm.

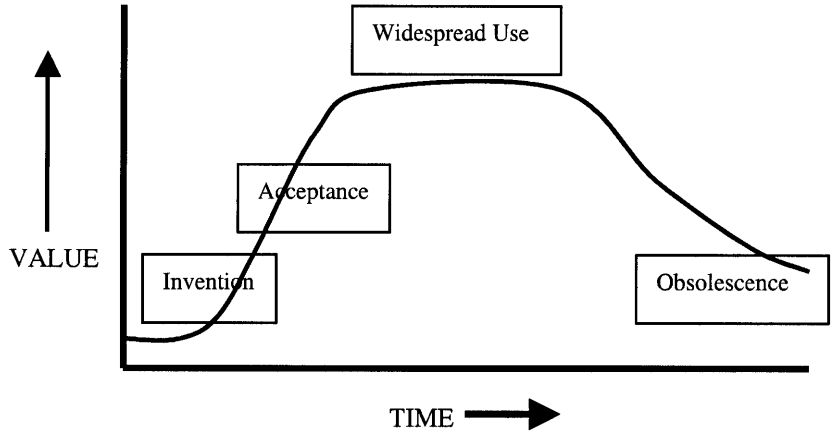

Figure 33.3. Typical Technological Acceptance Curve. The value of any product initially grows rapidly as it becomes widely accepted, then after a period of stable high value and widespread use, the product loses value as obsolescence occurs

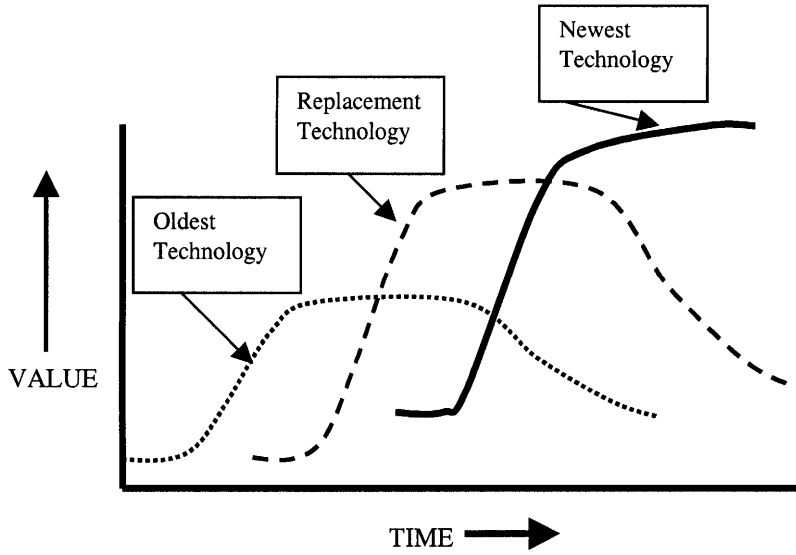

Figure 33.4. Technological Innovation produces a sequence of Technological Acceptance Curves. New technology replaces older technologies when clear benefits are seen

33.3 Societal demands on the geosciences

The Spa conference provided an important forum for participants from many different countries to interact, to discuss common problems, and to consider how to collaborate more effectively in the future. Informal discussions among participants ranged over many topics, but the focus remained on how the current situation affected research and application of 3D shallow subsurface characterisation.

There was considerable agreement concerning the current and anticipated future technological developments. The technology itself was not considered to be the major issue – rather, how to organise the projects and infrastructure to maximise the utility of these technologies was recognised as a major concern.

This led several discussions to explore how the current situation helped or hindered collaboration at the national and international levels. At the national level, the joint impacts of IT and societal trends on the missions and activities of various national geological surveys were accepted as important considerations. At the international level, discussions at Spa revealed some potentially interesting initiatives. The Spa discussions appear to have also promoted some new initiatives.

Since the assessments of the current situation naturally laid the foundations for proposals for future directions, the current national and international situations will be described below, while the future directions are discussed in the concluding section of this chapter.

33.3.1 The role and status of National Geological Surveys

National Geological Surveys (NGS's) were established in the 19th century to provide consistent strategic information concerning geology and resources that would aid in economic development to their governments, and thus to their societies. While that rationale remains true, in most cases the critical societal issues have changed dramatically – especially in the past decade or so. Increasingly, NGS's have been asked to respond to the perceived breakdown between their stores of earth science data, information, and knowledge and society's access to this knowledge.

Major societal issues are frequently grouped under the term "sustainable development." There is a broad consensus concerning the validity of the following statement contained within the latest Strategic Plan of the British Geological Survey:

"The interaction of society and natural environment produces uncertainty and risk. This creates major environmental challenges for sustainable development." (British Geological Survey, 1999)

Each NGS exists within a unique social, scientific, and economic environment – thus each is implementing unique strategic initiatives. Many are undergoing rapid transformations from science-driven, hierarchical organisations to user-focused project-management-based organisations. Underlying these changes is a broad consensus that IT technology, and especially 3D and 4D modelling tools, are the key to making appropriate predictions to societal problems that reflect earth sci-

ence realities. They recognise that future societal support of their missions depends upon their use of tools and methods for:

1. the collection, storage, retrieval and processing of geo-spatial data,
2. the dissemination and use of these data, and
3. the structuring, organisation and management of geo-spatial information production processes in an institutional setting.

This recognition is illustrated by the following quotations:

"In the future, information (and knowledge) management at the USGS should shift from a more passive role of study and analysis to one that seeks to convey information (and knowledge) actively in ways that are responsive to social, political, and economic needs." (National Research Council, 2001)

"Without mastering geoscientific knowledge management, geoscientific research would remain on a relative low grade of 'information processing'." (Netherlands Institute of Applied Geoscience, 2001)

"The understanding of earth science is greatly enhanced by the ability to visualise earth models in three-dimensions. Computers can bring these models on to people's desktops by providing detailed pictures in real-time. A range of information is associated with such models, describing and qualifying them: this information will include descriptions of the rocks comprising the models, their geotechnical and hydrogeological properties, and information on the way in which the model was constructed and its reliability." (British Geological Survey, 2001 pg.36)

From these few examples, which are but a small sample of similar statements, it is obvious that there is a strong symbiosis between the needs and goals of NGS's and those advancing 3D shallow subsurface characterisation.

Representatives from several NGS's were in attendance at the Spa conference. Additional delegates had worked closely with other NGS's and were able to share experiences. During and following the conference, discussions continued concerning how the common needs and experiences of various NGS's could influence the advancement of 3D characterisation of the shallow subsurface. The results of these discussions are included in the section defining the infrastructure and networking required to support the technological research agenda.

33.3.2 Current international initiatives and programmes

As might be expected, many aspects of the programmes being promoted by the international community mirror national concerns exemplified by the NGS issues described above. Several international initiatives are underway outside the earth sciences. The Geovisualisation projects of the International Cartographic Association (ICA) Commission on Visualisation and Virtual Environments represent an important example of such international endeavours, and are discussed below.

Within the geoscience arena, two international programs must be considered; the activities of the International Union of Geological Sciences (IUGS) and the hydrology and geoscience programs supported and promoted by the UNESCO Division of Water Sciences (and its International Hydrology Program) and the UNESCO Division of Earth Resources.

Dr E.F.J. de Mulder, President of the IUGS, attended the Spa Conference and shared his perspectives (see de Mulder and Kooijman, *this volume*). His current "Presidential Perspective," available on the IUGS Web-site [http://www.iugs.org/iugs/news/presms09.htm], refers to the issues expressed at Spa:

"At some locations we know so much about the subsurface, that with the assistance of GIS, new found transparency has enabled our engineers to construct cheaper but more solid foundations for our highways. Regrettably, not much of this exciting new knowledge has reached the minds of our politicians to date. .... Such ignorance occurs at a big expense to society. Billions of Euros and tens of thousands of lives are lost every year due to such ignorance." (IUGS Presidential Perspective, 2002)

The IUGS has just recently announced a new initiative to launch an "International Year for Planet Earth," that will be proclaimed jointly by the United Nations and the IUGS. Current plans call for this event to start at the International Geological Congress in Florence (Italy) in 2004 and proceed well into 2007. The science program will address many issues, but these include geoscience knowledge management and shallow subsurface characterisation. All topics comprising the Year for Planet Earth will have a significant outreach component and a clear human dimension.

IUGS proposals and activities are conducted in co-operation with United Nations programs. Following the Spa Conference, several discussions have been held with UNESCO personnel in Paris. The following statement exemplifies the common interests in geoscience knowledge management and 3D shallow subsurface characterisation within the UNESCO Division of Water Sciences (and its International Hydrology Program) and UNESCO Division of Earth Resources:

"UNESCO will act as a knowledge broker for effective sustainable development. Special emphasis will be given to strengthening international scientific and intellectual co-operation and networking, leading to a sharing of knowledge, information, and best-practices; producing and disseminating scientific knowledge... ; broadening access to information and knowledge ... ." (UNESCO, 2002)

33.4 Current research in geovisualisation

In March 2002, an ESF Euroconference on the theme of 'Geovisualisation' took place in Albufiera, Portugal. This conference occurred less than a year after the ESF conference held in Spa, Belgium and described in this publication.

The Albufiera conference was part of a series of conferences inspired by the activities of the International Cartographic Association (ICA) Commission on Visualisation and Virtual Environments. MacEarchen and Kraak (2001) provide some background on the activities of this ICA Commission. Further information is available at the Commission Website {www.geovista.psu.edu/icavis}. This Commission's approach in developing a comprehensive geovisualisation research agenda may serve as a model for similar activities in 3D shallow subsurface characterisation.

In 1995 the Commission identified and began to address core research problems associated with extending cartographic methods into an increasingly dy-

namic technological environment. A second, equally important, charge was to identify complementary research efforts in computer graphics, information visualisation, exploratory data analysis (graphical and computational statistics) and related fields and develop mechanisms for co-ordination between these and cartographic visualisation efforts. In many respects, concepts raised at the 2002 Geovisualisation Euroconference reinforce the discussions and conclusions reached at the earlier Spa Euroconference. Three observations from the Geovisualisation Euroconference in Albufiera are especially pertinent:

1. There are much more powerful tools available than 10 years ago.
2. Understanding the research challenges is getting better and more precise.
3. Understanding basic human experiences and cognition skills is growing.

'Geovisualisation' was approached from a broad range of disciplines that deal with presenting geospatial data – physical geography, surveying, cartography, economics and computer science. The conference organisers defined 'Geovisualisation' as the use of computer supported interactive visual representations of (geospatial) data to strengthen understanding. They stated that the primary purpose of geovisualisation is to provide *insight*. Use of visual geo-spatial displays can help explore data, create hypotheses, solve problems, and create and disseminate knowledge – leading to discovery, explanation, and understanding of natural or socio-economic processes. Such understandings can support decision-making.

33.4.1 The geovisualisation research agenda

The Geovisualisation Euroconference in Albufiera expanded upon earlier cross-cutting challenges identified by the ICA Commission and described by MacEarchen and Kraak (2001). The numerous explicit issues raised at this Euroconference may be summarised in three categories:

1. ***Enhancing Representation (extension of cross-cutting challenge 1)***

   - 3D modelling techniques must be chosen so as to suit user's needs.
   - Increased use of state-of-the-art real-time rendering techniques may improve 3D modelling.
   - Some virtual reality (VR) and augmented reality (AR) techniques have evolved to the state where they can usefully assist in the visualisation process.
   - Incorporating temporal information into '4D'models can improve geovisualisation.

2. ***Extendable Tools to Enhance Public Participation (extension of cross-cutting challenge 2)***

   - The effective use of metadata is important.
   - Existing interactive exploratory tools can enhance the ability of maps to assist with visual thinking, and support decision-making and data analysis.

- Technology development and its relation to the ability of the public to participate in the geovisualisation processes.
- Whether, or not, models can, or should, accurately represent the 'real world.'
- How the choice of methods and techniques affects the situation being studied.

3. ***New Geovisualisation Tools to Support Group Work (extension of cross-cutting challenge 3)***

   - A multi-disciplinary approach where the different parties communicate is required.
   - Establishment of geo-collaborative environments will assist in the effective production and use of modelled scenarios.
   - The cognitive-semiotic relationship in the modelling process and the model itself is important.

By examining these research issues, the Geovisualisation Euroconference in Albufiera identified 7 priority research questions:

1. How can we get from data to knowledge?
2. What are the user needs?
3. How can better systems be developed using algorithms, techniques, and architectures?
4. How can we best benefit from technologies?
5. What is the 'vocabulary' of dynamic multimedia visualisation?
   - Should it include standardisation, interaction or new symbols?
   - How should this vocabulary be used?
6. What should the data 'know' about how it is best presented?
   - How should metadata, guidelines, context, and semantics be utilised?
7. What exists in the world that needs to be represented?

As noted subsequently, these may be considered to form the basis for a technological research agenda that is remarkably similar to the technological research agenda defined a few months earlier by the geoscientists attending the Spa Euroconference (Evans, *this volume*).

33.4.2 The ICA Research Network Operations

Both Euroconferences (2001 in Spa and 2002 in Albufiera) were just the latest in two parallel and lengthy series of conferences. Importantly, the Geovisualisation Euroconference inAlbufiera was able to build on a legacy of international research encouraged and directed by an established international network through the ICA Commission, notably concerning the research agenda. Teams of researchers have been assembled internationally to address four themes:

1. Represent geospatial information,

2. Integrate visual and computational methods of knowledge construction,
3. Interface design for geovisualisation environments, and
4. Cognitive/usability aspects of geovisualisation.

The teams include both Commission members and others active in geovisualisation and related areas. Participants represent a range of disciplines and include representatives from government and the private sector as well as academic researchers. Outreach was enhanced when the Commission co-operated with an industry-sponsored group – the ACM SIGGRAPH organisation – to undertake a three-year joint project. A series of publications reported the results of a series of international meetings and workshops (MacEachren and Kraak, 1997; MacEachren, 1998; Kraak and MacEachren, 1999).

33.5 Impediments to subsurface characterisation

Discussions during the Spa conference identified four major impediments to the greater use of subsurface geological modelling:

1. The lack of fully developed 3D and 4D oriented mathematical, cognitive, and statistical spatial analysis tools.
2. The inability of available systems to encapsulate the natural variability of geological features, or to represent and accurately depict uncertainties related to interpretation of spatial configuration or properties.
3. The broad lack of access to specialised tools for exploring and modelling geological systems. Other than those developed for the oil industry; these are generally too expensive or commercially sensitive for all but a few organisations to procure.
4. The paucity of comprehensive examples that might overcome what may be termed 'geoscientific inertia'. Many geoscientists are aware of quantitative subsurface characterisation methods, but the majority do not embrace them because they have yet to be convinced that the investment in time, effort, and funds will yield a dividend or result in better science.

33.6 Strategy for overcoming impediments

Discussions among participants at the Spa conference suggested that it may be possible to overcome some of the impediments defined in the previous section by:

1. Exploring cross-disciplinary applications of geological modelling and computing science to ground characterisation through dialogue between providers and users
2. Establishing how subsurface characterisation methods could be made easier and more productive

3. Establishing a network of centres to provide the critical mass needed to realise the full potential from co-operation, synthesis, integration, and innovation in the search for better prediction protocols
4. Encouraging young researchers to explore cross-disciplinary knowledge and experience within their specialised research project.

These recommendations emphasised the importance of encouraging two complementary research agendas – one research agenda would focus on technological developments while the second agenda would focus on implementation issues. Success in promoting enhanced application of geological subsurface characterisation depends on achievements in both research agendas.

33.7 Research concerning technological issues

The characterisation of the shallow subsurface is a complex issue, involving consideration of many factors. Deliberations at the Spa conference identified eleven topics that formed the basis for a technological research agenda:

1. Standardise digital data collection, storage and processing
2. Develop accessible databases, including metadata
3. Disseminate information
4. Establish a network of geoscience modelling providers
5. Communicate and collaborate between interested parties
6. Change the focus towards user needs: user's problems should drive the modelling process
7. Ensure the model effectively incorporates the geoscientists' expert knowledge, and is presented in an appropriate manner
8. Develop relevant new modelling software and processes
9. Validate and audit models to ensure their relevance
10. Effectively incorporate uncertainty, in data and model
11. Provide geoscience teaching and learning through higher education institutions in partnership with national surveys.

These topics, and thus the technological research agenda derived from the Spa conference, closely align to the geovisualisation research agenda described by the ICA Commission at the Geovisualisation conference. The two research agendas are mutually supportive and suggest that future research collaboration between geoscientists and geographers should be encouraged.

33.8 Networking to support the research agenda

Several participants of the Spa Conference, including representatives from several National Geological Surveys (NITG-TNO, BGS, BGR, GSC, and USGS), as well as international organisations and research institutions (IUGS, ITC, IHE, Nottingham Trent University, and Colorado School of Mines) have formed a core group

of international scientists who are emphasising a pragmatic, tactical, and application-oriented approach to the formalisation of techniques and protocols for the geoscience community. Group participants have briefed their management on the developing co-ordinated effort. Considerable common ground has been established and the basis for technical cooperation has been determined.

Their personal experiences have led to the conclusion that computer technology alone cannot enable geoscience knowledge integration. Rather they emphasise the human-computer interaction that must be supported by a 'geoinfrastructure' that contains integrated, formalised, and fully documented protocols (O'Brien, et al., 2002). They define a 'protocol' as equivalent to a 'business process' and specify that protocols contain the rules that define the data flow, sequencing of events, techniques, and standards that integrate various inputs to create a measurable output. In this regard, they are following concepts espoused by the British Geological Survey (Smith, *this volume*), as well as many others. In co-operation with research undertaken at Los Alamos National Laboratory, these concepts are being implemented within prototypical computer-based information management tools (Nasser *et al.*, *this volume*).

This prototype demonstrates that it is appropriate for the geoscience community (public, private, and academic) to engage in a co-ordinated effort to capture and improve elements of this emerging paradigm. The core group has recognised that further international collaboration is needed to develop a stronger and more robust protocol (D'Agnese and O'Brien, 2002).

33.9 Research agenda for developing protocols

Although the existing use of IT tools have greatly impacted the organisational models of National Geological Surveys (NGS's), widespread realisation of the perceived benefits of these IT tools requires the establishment of, and adherence to, a protocol that can provide quantitative predictions to societal questions with verifiable accuracy. The protocol must extend well beyond the limited aspects of process and predictive model validation and verification to encompass the entire sequence of geoscientific data, information and knowledge management. Development and adoption of this protocol is a prerequisite to producing timely and cost-effective solutions to societal problems that reflect earth science realities. Timely and cost effective solutions are required if the geo-information is to be routinely considered in society's decision-making process (D'Agnese and O'Brien, *this volume*).

During the past decade, several European NGS's, as well as Canadian, American and other international NGS's, have gained considerable experience with applying existing "off-the-shelf" commercial technologies to create 3D subsurface geologic framework models. These models have been developed for a variety of geological situations at various scales and levels of geologic complexity. Large advantages have been demonstrated when such 3D subsurface models have been linked to numerical models of physical processes, specifically ground-water flow

models, to provide specific and quantifiable answers to decision makers. For example, the integration of geospatial databases, 3D geologic framework and ground-water flow models developed by the U.S. Geological Survey scientists on the Death Valley Regional Ground-water Flow System Project are an excellent example of applying these technologies and protocols to address the immediate radioactive waste management and environmental remediation concerns of a nationally important client – the U.S. Department of Energy (D'Agnese et al., 2002).

However almost all existing examples of 3D subsurface characterisation utilise software largely developed for use in petroleum exploration. Such software is too expensive and difficult to use for most NGS applications. Widespread future use will require "Faster, Better, and Cheaper" methods of performing these types of complex analyses.

33.10 Establishing the future international network

The previously described core group of international scientists has effectively become a nucleus for an international research network. The interests of the core group revolve around their joint interests in 3D subsurface geological characterisation, but the research agenda has broadened beyond 3D geological models to include the applications of geospatial information management. Thus the core group is promoting the establishment of a "Global Geoscientific Knowledge Network" that will support the research required to define and establish the required protocols, infrastructure, and technological tools (D'Agnese and O'Brien, 2002). Their proposals reflect their observations concerning the reality of the current dichotomy between the geosciences and IT and the need to adopt a new paradigm to resolve it.

It appears entirely appropriate for NGS's to be intensively engaged in the coordinated effort to establish the "Global Geoscientific Knowledge Network" since they are a prime shaper of geoscience information standards in their respective countries. Several NGS's are currently undertaking important individual research programs, but no single NGS has the financial resources or knowledge-base necessary to rapidly develop a complete protocol. By sharing their experiences and responsibilities, a stronger, more robust, protocol can be developed and tested in a greater variety of operational environments. A better protocol will emerge.

33.11 Potential network partners

The development and implementation of this "Global Geoscientific Knowledge Network" will profoundly influence how the geoscience community conducts business in the 21st Century. In this regard, the research agenda being promoted in the closely-aligned geography discipline by the ICA Commission on Visualisation and Virtual Environments (MacEarchen and Kraak, 2001) is especially pertinent. There appears to be a case for further collaboration between the ICA Commission

and the geoscientists. The operational methods adopted by the ICA Commission also provide a useful model for how the proposed "Global Geoscientific Knowledge Network" might evolve.

There are considerable advantages to establishing an internationally accepted protocol:

1. Many societal issues transcend political boundaries; thus, mandating facilitation of data sharing.
2. Common protocols enlarge the "customer base" for the geoscientific community and make the "geoscience business market" more attractive to commercial software providers.
3. A more closely aligned geoscientific community results in a more efficient, socially-relevant, and marketable geoscientific knowledge-base.

Substantial funds must be obtained if the technological research agenda is to be addressed. Support of technological research appears to be the role of government-industry-academic partnerships. The experience of the ICA Commission on Visualisation and Virtual Environments, especially its joint research with SIGGRAPH support, is instructive and shows that such jointly supported research can be successful. There are very few opportunities for internationally funded research on these technologies, but there are several nationally funded opportunities that would allow NGS's to collaborate with academic and industrial research teams. For example, within the United States there are research opportunities supported by the National Science Foundation that could support the technological research agenda issues defined earlier. Similar opportunities exist in the United Kingdom and other European countries, as well as within the European Union science programs.

The dependency on nationally focused technological research programs, as defined above, places even greater importance on international collaboration and technology transfer. Multi-national organisations such as the European Science Foundation are well placed to assist in the development of structured conference series. Other scientific and professional societies can also provide mechanisms to encourage collaboration and networking.

Support and communication for promoting the infrastructure and protocols must involve a much larger community. The support of organisations, such as UNESCO, and international development institutions, such as the World Bank, must be sought to develop technology transfer channels. Some of these contacts have already been made with positive results.

The IUGS can provide some important forums to discuss and disseminate this protocol concept and the associated various technical components. The IUGS can provide international exposure to these concepts and organisational infrastructure needed to encourage widespread implementation. The IUGS cannot directly fund the actual developments, but can act as an "honest broker" in facilitating collaboration and technology transfer. The proposed "International Year for Planet Earth" can provide such an impetus.

The proposal to establish a Global Geoscientific Knowledge Network to foster a sharing of experiences and responsibilities reflects these realities. By allowing a

community of like-minded individuals to work on various pieces of the geoscience knowledge integration protocol, such a network would not only produce a more effective protocol, it would allow a more closely aligned geoscience community to emerge that could deploy the new paradigm on a global scale.

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